TOOLS FOR ASSESSING STUDENT LEARNING IN MECHANICAL DESIGN COURSES

Dónal HOLLAND[1], Conor J WALSH[2] and Gareth J BENNETT[1]
[1]School of Engineering, Trinity College Dublin
[2]School of Engineering and Applied Sciences, Harvard University

ABSTRACT
Assessing student learning and evaluating the effects of innovation in teaching remain a challenge for design educators and researchers. This paper describes the development of a set of assessment tools for use in evaluating pedagogical improvements in project-based mechanical design courses. An ethnographic study was undertaken to identify the design concepts and skills that students struggle to learn or apply. Four categories of concepts were identified as difficult for students: problem definition, evaluation of concepts, communication and comprehension, and prototyping strategies. In order to support interventions to improve students' learning in these areas, an assessment tool was designed and pilot tested with expert and novice participants. The results from this test will be used to develop an inventory of questions that can be used by educators and researchers to monitor student learning in mechanical design courses, and evaluate the efficacy of new teaching methods and tools.

Keywords: Mechanical design, assessment

1 INTRODUCTION

Research in the field of design education aims to inform the development of curricula and learning resources in order to improve student learning. Evaluating the effectiveness of these educational interventions requires assessment instruments that can provide feedback on students' understanding of the concepts and skills required for successful design. However, there is a lack of such instruments for design education, resulting in difficulties in evaluation. A survey of 273 research papers describing engineering design courses found that 40.7% of papers either did not provide any evaluation of effectiveness or did not provide any data to support conclusions [1]. Of the papers that included some reflection on what worked well and what needed improvement, 12.4% mentioned the difficulty of judging effectiveness.

This paper describes the ongoing development of an assessment tool for use in the study of engineering design education. The difficulty in evaluating effectiveness is related to the general challenge of assessing design knowledge. In the paper, we first describe current approaches to assessing design knowledge and then present an ethnographic study that was used to identify the concepts and skills that a useful assessment instrument should focus on. Based on these results, we describe the initial development and testing of a new assessment tool. The paper concludes with a description of the planned future work.

2 ASSESSMENT TOOLS FOR ENGINEERING DESIGN EDUCATION

Current approaches to assessing design knowledge generally focus either on the results of students' design work, or on their responses to sets of open- or closed-ended questions [2]. In the majority of courses described in the literature, the evaluation approach appears to be assessment of students' final designs or written reports [1]. This approach is attractive to educators as it involves activities that are already integrated into most courses. However, the success or failure of a design does not necessarily reveal anything about the learning that has taken place. As pointed out by Bailey and Szabo (2006), assessment approaches should focus on the design process, rather than the quality of the end result [2]. Strategies to overcome this limitation include reviews of student portfolios and regular meetings between instructors and design teams [4]. However, these approaches are very time-intensive, and are often not feasible in large classes.

Some educators use closed- or open-ended questions to probe student understanding. Okudan et al. (2007) developed the Comprehensive Assessment of Design Engineering Knowledge (CADEK) instrument, a mix of open- and closed-ended questions to measure the skills and knowledge covered in introductory engineering design courses [4]. Sims-Knight et al (2005) developed a computer simulation in which students could advise a fictional design team by selecting options from a list of possible courses of action [5]. Closed-ended questions such as multiple choice problems have the advantage of being easy to score in a consistent and objective way. However, they are of limited use in inherently open-ended fields such as design.

Answers to open-ended questions can be more challenging to assess but also more appropriate for gaining insight into procedural skills. Shah et al (2012) are currently developing a battery of standardized tests to assess a range of design skills [6]. To date, an 8-item test focused on divergent thinking has been developed. Many open-ended approaches involve asking students to describe or comment on the design process. Frank and Strong (2010) asked students to describe the steps they would take to design a solution to one of three given problems [7]. Bailey and Szabo (2006) asked students to critique a proposed design process [2]. These approaches test students' declarative knowledge of design process principles, for example by asking students to describe the elements required for effective teamwork [4]. However, it is one thing to be able to describe an ideal design process as taught in class, and another to actually follow it in practice.

Current efforts to develop design assessment tools show promise for improved approaches to understanding student knowledge. For our purposes however, there are two major drawbacks to the approaches described here. The first is that they focus on knowledge that is taught in the current curriculum. For example, in the pilot study of the CADEK instrument the majority of students assessed agreed that any person taking the course should be able to answer all of the questions on the test [4]. This is unsurprising, and indeed it is only fair to students that tests developed for use in a course should reflect the material covered in that course, especially if these tests have an influence on grades. However, the aim of much research in design education is to identify important concepts and skills that are not covered in current curricula, and propose methods of incorporating these topics into teaching. For example, estimation has been highlighted as a skill that is essential to design practice but consistently neglected in engineering programs, and some have suggested new activities to introduce this topic into the curriculum [8]. When evaluating such changes, many of the tools described here can be of limited usefulness due to their focus on existing curricula. If we only test what we teach, we will not gain any understanding about the topics we are neglecting.

The second major drawback to existing assessment tools is that most of them are time-consuming for both students and educators. In order to provide real-time and ongoing feedback that can influence teaching and research, the ideal instruments would be capable of being delivered via short in-class exercises. Examples of such an approach can be found in physics education, where educators have redesigned courses guided by the use of assessment tools such as the Force Concept Inventory, a collection of conceptual questions that test student understanding of fundamental mechanics concepts [9]. In the Peer Instruction approach described by Crouch and Mazur (2001) classes are structured around conceptual questions that students answer individually and in groups [10]. Student responses to these short exercises provide insights into how students are thinking and whether they are achieving learning goals. Efforts to develop concept inventories for engineering education have to date focused on engineering science subjects which are well-suited to closed-ended, well-defined problems (e.g. [11]). Conceptual questions in design are more likely to be open-ended, ill-defined problems with no unique correct answer.

In the next section, we attempt to identify some of the topics that could be covered by conceptual questions for engineering design. By identifying the knowledge that proves difficult for students in design courses through empirical study, and basing our assessment tools on these results rather than on stated learning outcomes alone, we hope to develop a tool that will stimulate and support curricular innovations.

3 DESIGN KNOWLEDGE

3.1 Modelling the expert designer

Research conducted by cognitive psychologists and design engineers has identified some of the behaviours and attributes that differentiate expert designers from novices. The results of these studies indicate that experts possess both comprehensive content knowledge and domain-independent general process knowledge. Their content knowledge includes an extensive, well-organized knowledge of specific design problems and solutions that can be used to draw analogies and identify or evaluate possible solutions to novel challenges [12] [13]. Their general process knowledge includes topics such as problem-solving strategies and process-management skills. Experienced designers engage in a more iterative process and gather more information at all stages of the process [14]. They are more likely to question the validity of received information, and when their content knowledge is not sufficient to address the problem at hand they employ alternative approaches including trial-and-error investigations of potential solutions [12] [13]. These results can inform our search for the essential concepts and skills that we should support students in learning during project-based design courses.

3.2 Research design

A combination of surveys and ethnographic case studies was used to gather data in three mechanical engineering design courses in two institutions with the aim of answering the research question "what are the major difficulties faced by students in project-based mechanical design courses?" The courses were project-based and involved teams of students working with users to define a problem and design a solution to it. Applications ranged from surgical tools to communications technology and class sizes ranged from four to 40. Participants included students at all levels of undergraduate and graduate study.

A series of anonymous, open-ended questionnaires were completed by students at regular intervals throughout the courses. The questionnaires asked students to identify the problems and frustrations they were facing in the course, any unanswered questions they had or points they felt were unclear, and any resources they felt were lacking. An ethnographic case study approach was used to study the experiences of five of the student teams, in two of the design courses. This research was carried out by a teaching assistant on the courses. Several of the procedures recommended by Wallendorf and Belk (1989) were used to guide the research, including prolonged engagement, triangulation, debriefing by peers and member checks [15].

3.3 Results

The survey responses and the observation field notes were examined for recurring themes and patterns, and from this four categories of design concepts and skills that were problematic for students were identified: problem definition; communication and comprehension; evaluation of concepts; and prototyping strategies. It should be noted that a common theme throughout all of the observed difficulties was that of students struggling to tolerate uncertainty. Uncertainty and ambiguity are present in all realistic design activities, such as tackling an ill-defined problem, communicating a rough idea, estimating quantities, or selecting a manufacturing process. Below, each category of design concepts and skills identified as difficult is described in more detail.

3.3.1 Problem definition

In all courses studied, rather than being provided with a design brief, students worked with a client to identify a problem that they then attempted to solve. This required decomposing an ill-defined qualitative need into a set of quantitative functional requirements. Decomposing complex, messy problems into more manageable tasks is a general process skill employed by successful designers, and proved difficult for engineering students accustomed to dealing with well-defined analytical problems. In these analytical problems, students are usually given a simplified model of a system and asked to derive or solve a set of precise equations characterizing the system. In open-ended design courses, however, students must construct their own simplified models and make rough first order approximations. This involves making assumptions and guessing quantities, activities that are at odds with the students' previous experience of engineering. Finally, gaining a sufficient understanding of a problem in an unfamiliar domain required students to source, evaluate, and synthesize a large amount of information, which involved research skills that many students struggled with in the courses investigated.

3.3.2 Communication and comprehension

Throughout the courses, students struggled with skills related to communicating and comprehending information about complex three-dimensional systems. These skills were required in order to understand the problem space, gain a knowledge of the prior art, collaborate with other students and external clients, and work with vendors and manufacturers to prototype their devices. Specific skills that students struggled with included spatial and visual reasoning, describing design concepts, and producing clear documentation.

3.3.3 Evaluation of concepts

The primary bottleneck for all student teams was deciding between design concepts. This required an ability to assess the feasibility of potential approaches, identify the most likely failure modes, and design tests to evaluate the proposed solutions. As noted previously, expert engineers often rely on an extensive knowledge of potential solutions and an ability to identify which solutions are appropriate for a given problem. Not only is it a time-consuming and difficult task for students to compensate for their lack of practical design experience, this lack of content knowledge also makes it extremely difficult to practice analogical thinking.

3.3.4 Prototyping strategies

While all students had previously taken courses that covered topics related to materials engineering, manufacturing science, component selection and process management, the majority had covered these subjects in theory only. Working within real time and budget constraints to produce a working prototype presented multiple difficulties. With the exception of concept evaluation, the most time-consuming task for all teams was developing a feasible prototyping strategy. A recurring problem was students failing to design for manufacturability or incorporate off-the-shelf components rather than bespoke parts into their designs. This was despite the fact that the teaching staff provided advice on these topics throughout the courses.

4 DEVELOPMENT OF ASSESSMENT TOOLS

4.1 Tool specifications and composition

In this paper we have defined the goals of a new assessment tool, reviewed the current approaches to assessment, and identified four major categories of skills that are essential to mechanical engineering design but provide substantial problems to students. Based on this, we now define the specifications of a new set of assessment tools to address the needs of researchers in this area. The new tools should:

- Be composed of short conceptual questions that can be delivered during class, or before and after a specific intervention;
- Test students ability to apply their skills and knowledge, rather than testing declarative knowledge;
- Test knowledge of the four categories of difficult concepts and skills identified in the previous section; and
- Include open-ended questions which test students' ability to handle ambiguity

Thirteen types of question were developed to meet the specifications. Table 1 contains a description of each question type. Scoring rubrics and multiple example questions were designed for each question type. For many questions, a range of possible answers were acceptable. In an effort to make the questions as realistic as possible, actual problems encountered by students during the ethnographic study or real problems from public design challenges were used as the basis for questions.

4.2 Pilot testing and results

A pilot test was conducted with 11 participants, ranging in experience from undergraduate students to post-doctoral researchers with several years of design experience in industry. Typically, assessment tools are tested only using the target population, in this case students. However in this case a wider range of participants was chosen because, as stated previously, the focus of these tools is not on current student knowledge, but on the knowledge we should be aiming to teach in future design courses. All answers were given a score of either pass or fail. Conventional item analysis, guided by classical test theory, was used to identify the discrimination and difficulty of each question [16]. Discrimination, with a value between -1 and +1 is the difference between the proportion of high-performing participants who passed the question and the proportion of the low-performing participants who passed the question. In this case, the item discrimination was calculated for the difference between the "expert" group (those with many years of design experience), and the "novice" group.

Discrimination is based on the idea that, on a well-designed question, the experienced designers should perform better than the novices. A value for discrimination that is either negative or close to zero indicates that a question is not useful in determining design skills. Difficulty, with a value between 0 and 1, is the overall proportion of students who passed the question. Questions with a difficulty close to 0 or 1 can be considered too difficult and too easy, respectively. The most difficult questions, based on the item analysis, were those related to part selection and guessing quantities. The easiest question types on the test were those related to evaluating information and identifying failure modes. The question types with the highest discrimination values were those focused on visual communication and manufacturing process selection, while those with the lowest discrimination values were the question types identified above as too easy or too hard.

Table 1. Description of question types

Category	*Question type*	*Description*
Problem definition	Problem decomposition	Participants are presented with a design brief or a complex problem and asked to break it into smaller, well-defined sub-problems
	Making estimates	Participants are required to make a reasonable estimate of a quantity such as the mass of an object
	Modelling	Participants are asked to construct a simplified mathematical model of a system
	Evaluating information	Participants are presented with information related to a design problem and asked to evaluate its validity, e.g. by critiquing a proposed solution to a given brief
Communication and comprehension	Visual/spatial reasoning tasks	Participants are shown a 2D representation of a 3D system and asked to complete a task such as interpreting the motion of a depicted mechanism
	Visual communication	Participants are asked to create visual representations, e.g. by drawing a concept
Evaluation of concepts	Assessing feasibility	Participants are presented with a design brief and a number of proposed solutions, and are asked to choose the most feasible solution and provide a rationale.
	Knowledge and understanding of mechanisms	Participants are asked to describe a mechanism to achieve a common mechanical task, such as converting angular motion into linear motion.
	Analogical thinking	Participants are presented with a design brief and asked to list as many analogies as possible that might inspire solutions.
	Design of experiments	A design concept is described and depicted graphically, and participants are asked to design a set of tests to validate or improve the concept.
	Failure modes	Participants are asked to list the most important potential failure modes of a described design concept.
Prototyping strategies	Part selection	Students are presented with a design situation and a component catalogue page and asked to select the most suitable component.
	Manufacturing process selection	Students are presented with a drawing of a part to be manufactured, and asked to select a method of making a physical prototype for testing.

5 CONCLUSIONS AND FUTURE WORK

The assessment tools described here have been developed through empirical study of students engaged in team-based engineering design courses. The results of the pilot test have given some indication of which type of questions can usefully distinguish between different levels of design knowledge. The questions that scored poorly are currently being redesigned or replaced. Alpha tests of the redesigned questions will be conducted with cohorts of design students in multiple design courses, and the results from these alpha tests will be used to further refine the tools. Further tests will also be conducted with faculty members and professional engineers. Through the continued refinement of these tools, we aim to gain a deeper understanding of the difficulties faced by students in learning and applying design knowledge.

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