An assessment of student needs in project-based mechanical design courses

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An Assessment of Student Needs in Project-Based Mechanical Design Courses

Abstract

In response to a perceived lack of practical design experience for students, many universities have introduced new project-based courses to the curriculum. This paper describes an investigation of the pedagogical needs of students in three new design courses. The aim of this research is to inform the development of learning environments and resources for these and similar courses. A series of questionnaires was used to identify the difficulties faced by student teams working on mechanical design projects, and the resources they felt were needed to support their learning. An ethnographic approach was used to expand upon the results of the questionnaires. The needs identified relate to design skills such as analogical thinking, prototyping, experimentation, modeling and analysis, and reasoning about uncertainty. The paper concludes with a discussion of the implications of these results for instructional design.

Introduction

Hands-on design activities are increasingly common in engineering programs.[1, 2] The increased focus on design is largely due to reviews of curricula and surveys of industry that identified shortcomings in engineering education, including insufficient opportunities for students to develop creativity, to apply their technical and analytical knowledge, and to practice communication and teamwork skills.[3,4] Design courses are intended to address these shortcomings. According to a review conducted by Turns et al., engineering design courses are predominantly project-based and involve students working on teams to solve problems. [5] Common learning objectives for these courses include engineering fundamentals, teamwork and communication skills, data analysis, and experimentation. Cryptically, the most commonly stated learning objective is “design” itself. Beyond general skills such as teamwork, communication, and data analysis, what specific design abilities should project-based courses aim to teach?

Empirical studies of expert design behavior can provide more specific learning goals, as expertise is the result of successful learning. By studying students and experienced designers performing design tasks, it is possible to identify those behaviors and ways of thinking that differentiate experts from novices. The results of such studies indicate that design expertise consists of extensive domain-specific content knowledge and a set of general strategies for solving design problems. Experienced designers take a more iterative approach to design, gather more information about the problem, and are more likely to question the validity of received information. [6, 7, 8] They have an extensive, well-organized knowledge of specific design problems and solutions.[8, 9] When faced with a design problem experts draw on this knowledge to identify analogies and generate a set of concepts likely to solve the problem.[10, 11] Analogical thinking allows them to evaluate the feasibility of concepts. [8] When their understanding of potential solutions is insufficient they employ a number of strategies including trial-and-error investigations of potential solutions.[9] These results suggest more specific learning objectives for project-based design courses. Students need opportunities to study the design process, experiment with different strategies, practice analogical thinking, and develop an understanding of the feasibility of potential design solutions.

This paper describes some of the barriers to achieving these learning objectives in new design courses. The study described is part of a project to understand the needs of design students and develop solutions to support more effective teaching and learning. Commonly reported challenges for project-based courses relate to time and costs.[4, 5, 12] Students struggle to balance the high time demands of design projects with the requirements of other courses. Building and testing a physical system requires access to a range of tools, parts, and materials. Our goal is to develop curricula and resources that best make use of the limited time available to educators and students, and facilitate low-cost design-build-test activities. In this initial stage of the research we examined student learning in real educational settings in order to better understand the needs of students and identify directions for the development of solutions. A common set of needs emerged across the courses studied. These needs and their implications for instructional design are outlined. Potential solutions are discussed, and useful results from the literature are identified.

Research design

A combination of surveys and ethnographic methods was used to gather data. The surveys were a series of anonymous, open-ended questionnaires completed by up to 62 students at regular intervals during the courses. The questionnaires asked students to identify the problems and frustrations they faced, any unanswered questions they had, and any resources they felt were lacking. The responses were examined for recurring themes and patterns, and several problem categories were identified.

In order to verify these results and gain further insight, an ethnographic approach was used to study the experiences of five of the student teams. Ethnography involves prolonged observation by a researcher immersed in the day-to-day lives of a group.[13] The goal is to develop an understanding of the group or a related phenomenon as it exists in its natural setting.[14] The ethnographic approach was chosen as the most appropriate method because the focus of the research was student teams working in real classroom settings with a multitude of variables beyond the control of the researchers. The following procedures recommended by Wallendorf and Belk were used to guide the research: prolonged engagement and persistent observation, triangulation, debriefing by peers, and member checks.[15]

Prolonged engagement and persistent observation were used to develop a broad understanding of the context and the group before focusing on particular themes. One of us (Holland) was a teaching assistant for the courses studied. This role involved attending weekly meetings between each team and the teaching staff, coordinating laboratory sessions for all teams, and meeting with the students outside of teaching hours to assist with design, prototyping, and testing activities. This provided opportunities to observe student activities and carry out informal interviews with the students. The interviews focused on the frustrations of the students, the activities that they found difficult, the resources that they were using, and the information they required. All teaching assistants were expected to discuss such topics with the teams in order to support the students, so the dual role of researcher and teaching assistant was not problematic. The researcher did not have any influence over students' grades. The students were aware of this and were informed of the nature and purpose of the research being conducted.

Triangulation is a means of enhancing trustworthiness during data collection. Multiple sources of data and methods of data collection were employed in order to triangulate the results. Twenty students in two institutions were used as sources for the ethnographic data. Triangulation across methods was achieved by comparing the ethnographic data to the survey results. Observer triangulation was achieved by having a second member of the teaching team record their observations during meetings with the student teams.

Debriefing by peers and member checks involve discussing the emerging interpretation of the data with peers and with study participants in order to get feedback and critiques. At regular intervals during the project, the lead researcher discussed emerging themes with other members of the teaching team and with a social psychologist with expertise in design education. Feedback from these discussions was used to guide data gathering and analysis. Emerging themes were also discussed with several of the students, in order to probe areas of interest more deeply and to satisfy the need for member checks.

The dataset resulting from this research consisted of dozens of text files composed of paragraphs describing events or statements by students. Analysis of the data followed the process defined by Miles and Huberman: data reduction, data display, and conclusion drawing and verification.[16] The data was studied for examples of obstacles faced by students, that is, examples of students getting stuck on a problem so that they were unable to progress with their learning. Each paragraph that described such a problem was identified and these paragraphs were clustered around similar themes to create categories. By comparing the results of the surveys with the observation and interview data, the common obstacles encountered in the courses were identified.

The courses

Three courses were studied: a medical device design course in Harvard University; a general mechanical design course in Trinity College Dublin (TCD); and a design innovation course at TCD. All three were project-based courses and involved students working in small teams. This seems to be the predominant form of design course in engineering programs.[5] All of the courses studied are new, having been introduced or completely redesigned in the last two years.

The medical device design course ran for 15 weeks and was delivered to an even mix of undergraduate and graduate students, with 16 students working on four teams. Each team worked with a surgeon from a local hospital to identify a need and design a solution. The teams then created a detailed design which was used to produce a final working prototype. While the students could build rough models using machine tools to evaluate ideas, they were provided with a budget and expected to have the final prototype manufactured by a professional workshop.

The design innovation course ran for nine months and was taken by graduate students. Four TCD students worked with a student team at Stanford University and an industry sponsor to solve a problem set by the sponsor. As with the medical device design course, the students followed the design process from identifying needs to producing a final prototype using a provided budget.

The general mechanical design course was delivered to undergraduate students and ran for five months. Ten teams of four students worked with visually impaired users to identify a need and develop a solution. Unlike the other two courses, the students did not have a prototyping budget, but were provided with equipment such as a microcontroller to use in demonstrating and testing their design.

Results

The main obstacles encountered by all teams related to decision-making, from defining the design problem to selecting a material for their prototype. The students had little difficulty thinking of potential solutions but they struggled to decide between competing concepts. This was largely due to difficulty assessing the feasibility of potential designs. The students felt it was "really difficult to evaluate each possible [concept without] going into extremely detailed designs." They were provided with guidance and with decision-making tools such as Pugh Matrices[17], and were expected to provide justification for their choices. Despite this, they felt that their decisions were often essentially arbitrary. Even when a decision had been made, the teams often lacked confidence and struggled to move forward. Successful design requires a range of skills to assess feasibility and make decisions, including analogical thinking, building prototypes, carrying out tests, and analyzing analytical or numerical models. The barriers that students faced in learning and applying these skills are discussed below.

Analogical thinking

Analogical thinking requires knowledge of a wide range of examples to draw on, which students generally lack due to their inexperience. Their ability to practice analogical thinking was hampered by a lack of what Wilson and Blanco called "the equivalent in design of the words, grammar, and rules of language".[18] Some teams spent a long time "reinventing the wheel" by trying to design machine elements from scratch before eventually discovering by chance an existing mechanism that could be used as inspiration. These difficulties were due not to a lack of understanding of general engineering principles, but a lack of awareness of specific existing designs. The information required by the students was not available to them. Many students expressed frustration at their lack of knowledge and requested that more lecture time be dedicated to topics such as machine element design, material selection, and design for manufacturability. Lectures were in fact provided on standard machine elements, materials, and manufacturing processes, but the open-ended and divergent nature of the projects meant it was impossible to predict and address the specific topics required by each team.

Prototyping and testing

Due to their difficulties assessing feasibility, the students attempted to produce multiple prototypes and carry out a range of tests. However, limited time, resources, and budget were obstacles to obtaining useful results. Problems related to prototyping, such as access to equipment and materials, were encountered by all teams. Sourcing and selecting parts and allowing for lead times added to the time demands of the course. Finding and selecting a manufacturer or prototyping shop that could make the required custom parts or assemble the devices proved difficult. For students who are only familiar with conducting design exercises on paper or using CAD packages, being constrained by available materials and the realities of manufacturing processes was a new experience. Toward the end of the course some teams needed to completely redesign their solution in order to make use of off-the-shelf parts. Others struggled to find a feasible alternative to the expensive mass-manufacturing process required by their design. The students found it difficult to get a sense of scale when using solid modeling software; they often lacked an intuitive grasp of quantities and needed to see physical models to understand their own designs.

The teams performed tests whenever possible, but this was done in a haphazard way. Engineering students typically have a lot of experience conducting experiments but this usually involves following a procedure designed by the instructor. As a result, the teams struggled to design their own experiments. Each team was expected to produce an experimental plan as part of an assignment, but this plan was often subsequently ignored by the students. Most teams expressed frustration at a lack of access to testing equipment and access to people to take part in user testing and feedback.

Modeling and analysis

Another reason for students' problems assessing feasibility was their difficulty creating the analytical and numerical models required to analyze and predict the behavior of their system. When using finite element software they had difficulty setting boundary conditions. On a number of occasions the capacity of a load sensor was far exceeded during testing because simple analysis had not been carried out to predict the range of forces involved. The students had taken and passed numerous courses covering methods of engineering analysis, so were familiar with those topics. However, in order to make use of these analytical methods they needed to generate simplified models of complex physical systems, and this required making assumptions, guesses and estimates. Engineering education generally emphasizes methods for precise calculations and does not cover skills related to approximation.[19] As a result the students were not confident in modeling physical systems and making rough estimates.

Tolerating uncertainty

Finally, while the skills discussed here can help guide decisions, uncertainty is an inevitable part of the design process. Decisions must be made when the information available is incomplete or ambiguous. However, students in engineering science courses are used to being provided with all the information required to solve well-defined problems that have unique correct answers. Project-based design courses provide an opportunity for these students to practice dealing with messy, ambiguous problems with no single correct solution.

All teams struggled with uncertainty. When working with users to define the problem and identify possible solutions, the students often found it difficult to adapt their plans to changing circumstances and conflicting feedback, complaining of "having to scrap ideas that [they]'d worked on for hours." Even towards the end of their projects, having spent time dealing with uncertainty and learning about the design process, many teams still felt that there were definite answers being kept from them and expressed a desire for access to "more experts that have straight answers."

Implications for instructional design

This research identified common barriers to learning design skills. The difficulties faced by students in learning and applying these skills suggest directions for developing curricula and learning resources for design courses. Some potential solutions are discussed here.

The difficulties related to analogical thinking suggest that students need access to detailed descriptions of design solutions, ranging from individual components to entire systems. Information on a large number of successful designs would allow students to practice feasibility assessment through analogical thinking, while improving their knowledge of topics such as machine element design, material selection, and manufacturing processes. Such descriptions should include information on the context in which a particular solution is appropriate. Case study analysis, "mechanical dissection" and reverse engineering activities could meet this requirement.[20, 21, 22, 23] Lessons could be drawn from the development of case study resources such as the Engineering Design Instructional Computer System (EDICS) developed at MIT[18], or mechanism libraries such as the Kinetic Models for Design Digital Library (KMODDL).[24] The difficulty with providing such information in open-ended design courses is that it is impossible to predict the topics required by students ahead of time. This could be overcome by assigning design projects related to ongoing local research, thereby providing the students with access to researchers with expertise in the relevant problem area.

Analogical thinking also requires the ability to transfer learning from one situation to another. The ability to use analogies and to think flexibly about complex, ill-structured domains can be aided by developing multiple representations of knowledge.[25] This would mean presenting each solution or case study from multiple perspectives, for example, from the perspective of different stakeholders, or by focusing on different functional requirements. When practicing this skill, students need to be prompted to transfer their learning from one case to another.[26] Working with multiple representations may also help students become comfortable with uncertainty and ambiguity, by demonstrating that there is no perfect solution and what works in one context may not work for a seemingly similar problem. Text descriptions of cases are better suited to allowing this ambiguity than graphical representations.[27]

Design students need tools and guidance for building prototypes and carrying out tests. Difficulties in prototyping were caused by a lack of experience in selecting materials, parts, and manufacturing processes, and in working with vendors and manufacturers. Christie et al. have developed a tool to allow design teams to plan and strategically evaluate prototypes from an early stage, by helping them to approach prototyping in an expert-like way.[28] This resource could help compensate for students' lack of experience and increase their understanding of the prototyping process.

Physical testing equipment proved most useful in the courses observed, but virtual tools could provide a low-cost means of carrying out experiments.[29] However, the students had difficulty obtaining useful results from simulation tools, and needed clear guidance on setting boundary conditions and interpreting results.

Improved training in statistical methods would help to address students' difficulties with designing experiments.[30] An increased focus on statistics and probability in engineering education has also been proposed as a way to enable students to tolerate ambiguity and "reason about uncertainty".[19] However, this training is beyond the scope of individual design courses, and would in all likelihood require separate, dedicated courses.

Finally, in addition to the precise analytical methods commonly covered in detail in engineering science courses, students need to learn how to create simplified models of complex systems and make rough approximations of physical quantities. Shakerin provides a list of simple activities and assignments intended to help students develop an intuitive understanding of quantity and gain confidence in making approximations.[31] Linder and Flowers suggest having students solve open-ended, ill-defined analysis problems.[32] Mahajan has written textbooks on approximation techniques for science and engineering students.[33] These resources could be used to create lectures, class activities and assignments to improve students' modeling and analysis skills.

Conclusions

Through ethnographic research, we have learned about the frustrations, difficulties, and unmet needs of the growing number of students taking project-based design courses. These needs – for supporting analogical thinking, prototyping, experimentation, modeling and analysis, and reasoning about uncertainty – will be used to guide the development and testing of curricula and learning resources. Potential approaches to meeting these needs have been identified, and useful resources and teaching methods have been identified from the literature. The next stage of research will involve testing these concepts with students in design courses.

Bibliography

[1] Heywood, John. (2005) *Engineering education: research and development in curriculum and instruction*. Hoboken, NJ: IEEE Press. 283–310.

[2] National Academy of Engineering. (2012). *Infusing Real World Experiences into Engineering Education*. Washington, D.C.: The National Academies Press.

[3] Spinks, N., Silburn, N., & Birchall, D. (2006). *Educating engineers for the 21st century*. Henley Management College, The Royal Academy of Engineering, UK.

[4] Mills, J. E., & Treagust, D. F. (2003). Engineering education—Is problem-based or project-based learning the answer? *Australasian Journal of Engineering Education*, *4*(1), 16.

[5] Turns, J., Cardella, M., Atman, C. J., Martin, J., Newman, J., & Adams, R. S. (2006). Tackling the research-to-teaching challenge in engineering design education: Making the invisible visible. *International Journal of Engineering Education*, *22*(3), 598.

[6] Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education*, *96*(4), 359.

[7] Mullins, C. A., Atman, C. J., & Shuman, L. J. (1999). Freshman engineers' performance when solving design problems. *IEEE Transactions on Education*, *42*(4), 281 –287.

[8] Ahmed, S., Wallace, K. M., & Blessing, L. T. (2003). Understanding the differences between how novice and experienced designers approach design tasks. *Research in Engineering Design*, *14*(1), 1–11.

[9] Ball, Linden J., St.B.T. Evans, J., Dennis, I., & Ormerod, T. C. (1997). Problem-solving Strategies and Expertise in Engineering Design. *Thinking & Reasoning*, *3*(4), 247–270.

[10] Ball, L. J., Ormerod, T. C., & Morley, N. J. (2004). Spontaneous analogising in engineering design: A comparative analysis of experts and novices. *Design Studies*, *25*(5), 495–508.

[11] Ullman, D. G., Dietterich, T. G., & Stauffer, L. A. (1988). A model of the mechanical design process based on empirical data. *AI EDAM*, *2*(01), 33–52.

[12] Sheppard, S., Jenison, R., Agogino, A., Brereton, M., Bocciarelli, L., Dally, J., Faste, R. (1997). Examples of freshman design education. *International Journal of Engineering Education*, *13*, 248–261.

[13] Creswell, J. W. (1998). *Qualitative inquiry and research design: Choosing among five traditions* Thousand Oaks, CA: Sage Publications.

[14] Silverman, D. (2000). *Doing qualitative research. A practical handbook*. London: Sage Publications.

[15] Wallendorf, M., & Belk, R. W. (1989). Assessing trustworthiness in naturalistic consumer research. In Hirschman, E. C. (ed.). *Interpretive consumer research.* Provo, UT: Association for Consumer Research, 69–84.

[16] Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook*. London: Sage Publications.

[17] Pugh, S. (1991). *Total design: integrated methods for successful product engineering*. Workingham,, UK: Addison-Wesley.

[18] Wilson, D. G. and Blanco, E. E. (1991). EDICS: a multimedia tutor for engineering design. *Mechanical Engineering*, *113*(10), 74-79.
[19] Dym, C. L., Agogino, A. M., and Eris. E. O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. *Journal of Engineering Education 95*(1), 103-120.
[20] Hsi, S., & Agogino, A. M. (1995). Scaffolding knowledge integration through designing multimedia case studies of engineering design. In *Proceedings, Frontiers in Education Conference, 1995*. Institute of Electrical and Electronic Engineers.
[21] Rad, H. (2012). Reverse Engineering as a Learning Tool in Design Process. *119th ASEE Annual Conference and Exposition*, San Antonio, TX, 2012.
[22] Sheppard, S. D. (1992). Mechanical Dissection: An experience in how things work. *Proceedings, Engineering Foundation Conference on Engineering Education: Curriculum Innovation & Integration*, 6–10.
[23] Dalrymple, O. O., Sears, D. A., & Evangelou, D. (2011). The Motivational and Transfer Potential of Disassemble/Analyze/Assemble Activities. *Journal of Engineering Education*, *100*(4), 741-759.
[24] Lipson, H., Moon, F. C., Hai, J., & Paventi, C. (2005). 3-D printing the history of mechanisms. *Journal of Mechanical Design*, *127*, 1029–1033.
[25] Spiro, R. J., Feltovich, P. J., Jacobson, M. J., & Coulson, R. L. (1992). Cognitive flexibility, constructivism, and hypertext: Random access instruction for advanced knowledge acquisition in ill-structured domains. *Educational Technology*, *31*(1), 24–33.
[26] Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive psychology*, *15*(1), 1–38.
[27] Stenning, K., & Oberlander, J. (1995). A cognitive theory of graphical and linguistic reasoning: Logic and implementation. *Cognitive Science*, *19*(1), 97–140.
[28] Christie, E. J., Jensen, D. D., Buckley, R. T., Menefee, D. A., Ziegler, K. K., Wood, K. L., & Crawford, R. H. (2012). Prototyping Strategies: Literature Review and Identification of Critical Variables. *119th ASEE Annual Conference and Exposition*, San Antonio, TX.
[29] Klahr, D., Triona, L. M., & Williams, C. (2007). Hands on what? The relative effectiveness of physical versus virtual materials in an engineering design project by middle school children. *Journal of Research in Science Teaching*, *44*(1), 183-203.
[30] Wood, W. H. (2004). Decision-based design: a vehicle for curriculum integration. *International Journal of Engineering Education*, *20*(3), 433–439.
[31] Shakerin, S. (2006). The Art of Estimation. *International Journal of Engineering Education*, *22*(2), 273.
[32] Linder, B., & Flowers, W. C. (2001). Integrating engineering science and design: a definition and discussion. *International Journal of Engineering Education*, *17*(4/5), 436–439.
[33] Mahajan, S. (2010). *Street-fighting mathematics: the art of educated guessing and opportunistic problem solving*. Cambridge, MA: MIT Press.