Using Deficient Models as Scaffolds for Learning Engineering Concepts of Tradeoffs and Optimization

Chandan Dasgupta, Tom Moher, University of Illinois at Chicago, 851 S. Morgan, Chicago, IL 60607 USA
Email: cdasgu2@uic.edu, moher@uic.edu

Abstract: There is a need to teach core engineering concepts to elementary grade students. We present a novel approach using 'deficient model' i.e. a sub-optimal solution, to help students attend to design optimization and associated tradeoffs required to improve an engineering system. The nascent stage of this research prevents us from making conclusions. However, the framework highlights how distinct science education approaches can be synthesized and applied in the context of engineering education.

Introduction

The recent National Research Council reports (NRC, 2010; NRC, 2012) highlight the need for elementary grade students to understand engineering concepts like design optimization and tradeoffs. Considerably less attention has been paid to this age group, where such efforts could serve as a "mainline" function for promoting technological literacy and stimulating long-term interest in mathematics and science (Capobianco et al., 2011). One of the few initiatives focusing on this age group is Boston Museum of Science's curriculum – Engineering is Elementary (http://legacy.mos.org/eie). Further research is needed to explore additional pedagogies and mechanisms for teaching engineering concepts. We propose a new approach for helping elementary graders grapple with concepts of tradeoffs and optimization. Our approach draws on prior science education research using worked examples, negative examples and model-based learning.

Framework

Worked examples provide an expert's (correct) solution to a problem for the learner to study and emulate (Atkinson et al., 2000). When worked examples are presented before unsolved problems, they channelize students' problem-solving attempts in productive directions leading to efficient strategies (Chi et al., 1989; Ward & Sweller, 1990). Such examples can similarly be used for effectively guiding problem-solving activities in an engineering context. In contrast, *negative examples* provide incorrect ways of solving a problem. Such examples are effective in problem-solving contexts as they discourage snap design judgments, thereby increasing accuracy of solution (Smoke, 1933). They help students identify design limitations (Haack, 1972) and can potentially lead them to focus on design optimization as a problem-solving task. We also know that *model-based pedagogies* help students build subject matter expertise and epistemological understanding of scientific knowledge (Lehrer & Schauble, 2006; White & Frederiksen, 1998). We consider model to be a simplified physical representation of a system of phenomena that makes its central features visible so that they can be used to generate explanations (Harrison & Treagust, 2000). Model-based pedagogies are most effective when students themselves construct and critique a model (Coll, France & Taylor, 2005). However, use of a single model or one worked example leads to 'functional fixedness' (Furió et al., 2000) in the science education context or 'design fixation' (Youmans & Arciszewski, 2012) in the engineering context. Students believe that there is only one 'right model' for depicting a phenomenon accurately. Similarly, engineers limit the probable solutions to a problem because of an overreliance on features of example designs presented to them. To tackle functional fixedness, science education researchers prefer to use multiple models (Lehrer & Schauble, 2006). However, in the engineering context, multiple example solutions can reduce the range and accuracy of design solutions (Jansson & Smith, 1991; Linsey et al., 2010).

In view of these challenges, we introduce the idea of using *'deficient model'* – sub-optimal/inefficient design solution in the form of a physical model – for teaching design optimization and tradeoffs. As opposed to negative examples which represent incorrect solutions, a deficient model presents inefficient solutions requiring students to learn how to identify these deficiencies and optimize the design. Based on research with worked examples, a deficient model (a) shows students a (sub-optimal) sample solution, (b) provides a starting point, (c) provides a reference example for comparison, and (d) prompts students to develop rules that guide problem solving. Our approach also draws on limited research using negative examples by (a) showcasing inefficient solutions and providing a baseline for the students, (b) channelizing attention to limits of a design, and (c) countering design fixation and leaving exploration space open for students. We also use model-based pedagogy by having students analyze the deficient model and then construct an (emergent) optimal model.

Through this research, we will investigate how the use of deficient models as priming artifacts impact students' productive engagement with engineering concepts of tradeoffs and design optimization. Two types of deficient models will be used – Improvable model (inefficient but complete model that that can be optimized by modifying) and Partially optimal model (partially optimal but incomplete model that can be optimized by extending and modifying).

Activity

We will use the context of designing a home plumbing system for this research. Two upper elementary grade classrooms will participate in the study. One grade will work with the improvable model and the other will work with the partially optimal model. Students will be first asked to critique the sub-optimal model and then subsequently build an optimal model by modifying or extending them using a limited amount of construction resources (serving as design constraint). They will measure the values of design variables (pipe length and diameter) and then use a software simulator to investigate the effect of different design decisions on the outcome variables (pipe cost, water pressure, water flow). For example, replacing a 1-inch pipe with 3-inch pipe reduces drop in water pressure at the end of the pipe but also increases cost of pipe. Students organize such findings in the form of rules of thumb for later use while designing their own emergent optimal model. These activities give students an opportunity to understand the sub-optimality of the deficient model, investigate the consequences of those deficiencies, establish relationships between different variables in the system and explore ways of constructing an optimal model. The deficient model will be used as a reference model while students build their emergent model using the rules identified before. Students will determine the optimal length and diameter of pipe for their emergent model based on given design goal – build a model as cheaply as you can (within a fixed budget of $2000) yet meet the minimum pressure requirements set by the building engineer. We believe that these design constraints can trigger consideration of tradeoffs related to optimization decisions. Students will finally compare their improved model with the given sub-optimal model, share their design rationales and answer questions about the design that their peers might have.

Conclusions and Implications

The nascent stage of this research prevents us from making conclusions. However, the framework and design of the study has implications for the communities' knowledge of engineering education pedagogy. Two primary contexts encapsulated in the conference theme are 'engaging in epistemic practices' and 'engaging in design'. The research idea presented here espouses these contexts by facilitating student engagement with design tasks requiring them to make tradeoffs and optimization decisions, critical concepts in engineering discipline.

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