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Motivating Undergraduates to Use Their Engineering: Integrating COMSOL Multiphysics and Designs for World Health*

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Humanitarian engineering design problems can be used to motivate students to learn finite element analysis software. Specifically, health-related projects originating from needs in developing countries are assigned to teams of undergraduate juniors in Bioengineering, and COMSOL multiphysics is used to assess whether designs meet quantitative design criteria. Survey results suggest that this method is effective in helping students use engineering principles such as transport phenomena, heat transfer, and solid and fluid mechanics to assess feasibility of designs ranging from pediatric ventilators to electrosurgical pens. We conclude that the humanitarian engineering design theme motivates students to learn COMSOL multiphysics thus reinforcing technical and professional skills necessary to prepare them for modern engineering practice.

Keywords: finite element analysis; humanitarian engineering; bioengineering; biomedical engineering

INTRODUCTION

TEACHING DESIGN is one main focus of undergraduate engineering curricula [1]. Design has also been designated as a key component of accreditation by the Accreditation Board of Engineering and Technology (ABET) [2]. Despite its importance, however, design in many engineering curricula is relegated to a capstone course for seniors in which industry-sponsored projects are proposed to design teams and used to motivate students to learn the design process, although many schools are introducing design-related courses earlier and more often. Much anecdotal evidence suggests that many design teams neglect to use fundamental engineering principles in the design process, despite the consensus that engineering science should form the underlying foundation of engineering practice [3]. It is possible that design teams fail to use fundamental engineering principles taught to them in their more theoretical engineering courses, largely because it is difficult to apply these engineering principles to complicated geometries in which there are multiple interacting physical principles involved. Thus, students tend to favor strategies that require conceptual design, development of prototypes, testing, and redesign, despite the inherent inefficiencies of multiple prototype development. These methods persist despite the industry calls to implement computational simulation in iterative design.

Below we describe the integration of COMSOL Multiphysics and a problem-based thematic design course to address the main pedagogical challenges in bioengineering design. These challenges include attracting real life design problems in the classroom context, integrating advanced engineering tools into the iterative design process, and identifying a sustainable outlet for final design solutions. Specifically, we worked with Duke University's Engineering World Health (EWH) program to identify design projects appropriate for developing countries [4]. These projects represent design problems with potential real world impact. In addition, they are fairly simple conceptually, which makes their completion more feasible in a one-semester design course. COMSOL Multiphysics components were introduced in parallel with traditional design strategies to facilitate student integration of engineering principles and iterative design, and to test feasibility before prototype development.

We will begin with analysis of the pedagogical challenges and potential solutions using integration of problem-based learning [5, 6], finite element analysis, and design. We will then provide the details of our approach which will be useful in course design elsewhere. We will conclude with assessment methods and results used to assess the impact of this approach on undergraduate competency in design and finite element analysis (FEA).

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INTEGRATION OF SIMULATION WITH DESIGN SATISFIES ABET CRITERIA

With the rise in importance of ABET accreditation standards and the inherent conflicts that accompany scheduling courses and meeting outcomes, there has been a push toward more seamless integration of content and "soft skills" in the classroom [3]. This strategy of integration is evident in senior capstone design courses that entail open-ended problems, teamwork, presentation, and design. But because these design courses come at the end of the students' four years of college, often after they have been accepted to medical school, graduate school or industry, they do not impact students' career choices early enough. Thus a number of programs have moved toward integrating design into the curriculum at earlier stages. All engineering curricula at Penn State, for example, require a first year design course and some departments in engineering are adopting junior-level design courses. An advantage of junior-level design courses is that students have learned underlying engineering fundamentals that are not available in the first year. Nevertheless, engineering principles and design are often segregated. A cursory survey of senior design projects suggests that students are not using quantitative engineering principles in the design process, or in the evaluation step. Thus there is a fundamental disconnect between design principles and engineering science. This is the case despite progress toward establishing the engineering sciences as an underlying infrastructure for most engineering curricula [3]. It is the goal of the course described below to better integrate engineering principles into design through the motivating influence of humanitarian engineering.

GOOD COMPUTATIONAL SIMULATION SOFTWARE PROVIDES STUDENTS WITH TOOLS TO IMPLEMENT ENGINEERING PRINCIPLES IN THE DESIGN PROCESS

For undergraduates, engineering principles are difficult to implement in the design process because the geometries are too complicated, the relevant engineering principles are too difficult to implement because of non-linearity, or the relevant engineering principles have not been learned. These issues of complex geometries, non-linearities, and need for additional training in engineering are especially acute in bioengineering because of the inherent geometric complexities of biological systems and their many interacting physical principles. Engineering applied to biology and healthcare is inherently a multiphysics problem.

For five years, the junior design course in Penn State Bioengineering has been a theme-based integration of design and engineering science. Pedagogical support for theme-based classes has been reported recently [7] and we have extended this concept to encompass a whole course. Examples of themes have been: tissue engineering of a vascular graft, obesity and diabetes, and, most recently, humanitarian engineering.

Organization around a theme provides the benefits of connecting new material to known engineering and biological concepts. For example, for the tissue engineering of a vascular graft theme, there were a few introductory lectures on the biology of blood vessels, and the basics of biomaterials, but the main learning objectives were integration of solid and fluid mechanics, biology, and transport phenomena into the design process. It was not necessary to teach all aspects of tissue engineering. The more important objective was use of engineering principles to address an important and cutting-edge problem in healthcare. However, it was difficult to provide the required number of independent projects to teams (about 8–10 teams) consistently, semester after semester. Thus the course then moved toward rotating themes, the first of which was obesity and then humanitarian engineering. In general, rotating themes can help prevent excessive sharing of material among students from different semesters. However, the work load for the faculty organizing the course becomes excessive, and it is entirely possible that the themes are outside the faculty members' area of expertise.

As a case study to highlight the difficulties in integrating engineering science and design using industry-relevant projects, we focus on the design for an implantable leptin sensor to monitor the propensity for weight gain, which is an example of a project that addressed obesity issues. The projects originated from viewing a video of gastric bypass surgery on www.or-live.com. Although the goal of this assignment was to identify engineering needs for design projects, the students were subsequently allowed to brainstorm on any project related to obesity. In this case study the students thought that gastric bypass surgery patients could benefit by knowing the propensity to gain weight as indicated by leptin concentrations in the blood. By developing an implantable leptin sensor, the patients could be monitored using an unambiguous weight-gain indicator. The sensing would be through interstitial fluid since the sensor would be implanted under the skin. Furthermore, the detection mechanism for leptin was not yet available and the students designed a material interface for leptin capture and sensing. Relevant engineering principles were: transport of the leptin from blood to the interstitial fluid, transport through the sensor coating to the leptin sensor, analysis of leptin binding to the sensor, conversion of binding rate to electrical impulse, development of a mechanism to relay electrical signal to digital acquisition device, and methods to analyze the time-trace of signal to understand actual leptin concentrations, and understanding of the biological implications of leptin time traces on appetite.

Many of these design needs were not apparent initially and the time constraints of a one semester course meant that the students needed to focus the project on only one or two of the crucial elements. Because of this fact, student satisfaction in the usefulness of their efforts waned somewhat because the students did not have a sense of project completion. It may have been possible to find designs where teams of students could work on various aspects of one overall design, although this would have required heavy management overhead for the faculty member when coordinating intra and inter-team dynamics and progress. But we contend that the use of open-ended, non-industry sponsored projects in the junior year is fraught with problems of uncertainty in relevance of the design and it is difficult for faculty to evaluate the quality of multiple design projects addressing clinical needs outside the faculty's area of expertise. Nevertheless, the projects were amenable to computational simulation and were useful in this respect to encourage application of engineering principles to ambiguous but medially-relevant product design.

HUMANITARIAN ENGINEERING PROJECTS PROVIDE TOOL FOR INTEGRATING ENGINEERING SCIENCE AND ENGINEERING PRACTICE

The previous example outlines design projects as the essential way to integrate engineering science and practice, but often the available design projects are too routine because they do not originate from needs in society (industry or medicine). In addition, sponsored projects are often too difficult to be done by a team of undergraduates who do not have the necessary intuition gained from industrial experience. Finally, availability of design projects is limited. For the following semester we designated "bioengineering world health" as a design theme. As in the previous semester, the students needed to understand customer needs, but in this case the design projects came directly from those posted on the website of Engineering World Health (see Table 1). Thus the projects were guaranteed to meet customer needs, although the methods of meeting design criteria were still open ended [8].

Humanitarian engineering projects can provide a tool for integrating engineering science and engineering practice by providing a steady stream of needs [1]. These needs are communicated from humanitarian engineering professionals but once obtained the projects have the following qualities: They are often "easy conceptually" in that they can be analyzed using fairly simple engineering principles without serious compromise of product safety. Although safety is important, the projects are not overly burdened with regulations with which the students may not have familiarity. The projects arise from needs with which the students are familiar (e.g. hunger, thirst, need for clean water, and need for simple medical procedures). Although the extent of hunger, etc. is not always appreciated by students in more affluent countries, these projects can be contrasted with other procedures currently in practice in medical industry which require in-depth knowledge of the disease process, understanding of biomaterial interactions, detailed understanding of material properties of polymers, etc. Humanitarian engineering projects are introduced to students at an age where these issues may influence career decisions. Many student still state that they want to "help people" as a criterion for job selection. Although many students will not necessarily go onto careers in humanitarian engineering, the notion of helping people with severe problems and acute needs can be a powerful motivating tool (Thomas Colledge, personal communication) [9].

FINITE ELEMENT ANALYSIS SUPPORTS ITERATIVE DESIGN STRATEGIES INVOLVING COMPLEX GEOMETRIES AND DIFFICULT ENGINEERING PRINCIPLES

Finite element analysis provided a means to address engineering applications to complex geometries in which difficult engineering principles were required for analysis and design (see Fig. 1 and Table 2). COMSOL multiphysics is a relatively new FEA package that is PC / Windows based software and is designed to be "user-friendly" with intuitive graphic user interfaces and many of the detailed engineering decisions on FEA occurring behind the graphical user interface (GUI). This software provides tools which can introduce students to FEA in a half semester, sufficient for their informed use of the software. It can allow them to implement the software on engineering problems because it has good solid modeling capabilities that can interface with Solidworks™. It allows students to implement engineering principles with which they may not have formal training and provides easy access to multiphysics capabilities that will be required by most open-ended design problems. The software provides mechanisms for iterative design optimization through parameterization. Last, the software provides good post-processing tools that can be useful in demonstrating that a design meets criteria without having to actually develop a prototype of the project. Importantly, COMSOL provides detailed minicourses to assist students in learning the details of the software.

As a case study we focus on the design of a cold box for storage of medicine for transport to a remote location lacking a refrigerator (see Table 1 above and Fig. 2). In this project, the students needed to understand heat transfer from the cold box, the necessary temperature of the medicine and the ambient temperatures likely to be encountered during a typical trip. The engineering principles involved were the heat transfer by conduction and

Table 1. Humanitarian engineering problems: projects in which COMSOL multiphysics was used to assess if design met particular quantitative criteria are listed. Representative pictures of designs and analysis are shown. Web descriptions are from [4]

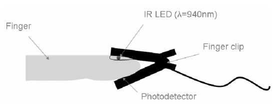
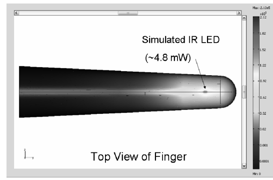
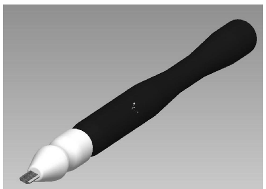
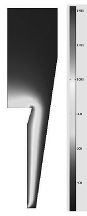
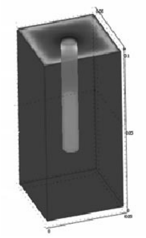
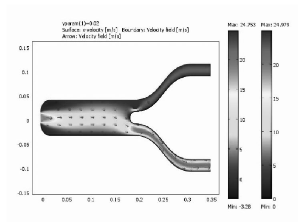
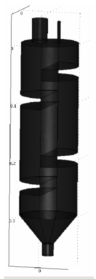
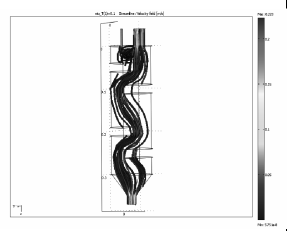
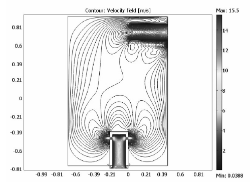
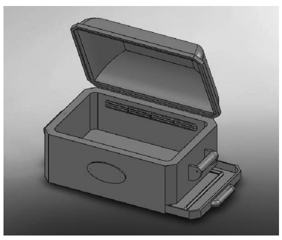
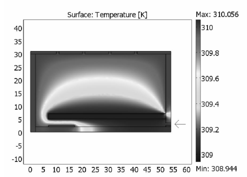
Project title	**Web description**	**Design Concept**	**Engineering Principles involved**
Pulse Oximeter for Heart Rate 	"The pulse oximeter is one of the most common medical instruments, and is the most frequently requested piece of medical equipment . . . The most important function is to display heart rate . . . The device must use non-disposable sensors. It should operate on a finger of an adult. . ."	LED and photodetector combination where changes in light transmission through the finger would result in detector pulsing. Goal was to analyze light fluency with the goal of using a less sensitive (and less expensive) photodetector	Minimum allowable photodetector sensitivity was determined by estimating fluency of light using the Helmholtz equation 
Bovie Pen Hardening 	"Electrosurgery is the most common form of cutting, . . . most developing world hospitals must re-use the same disposable bovie pen . . . This project is to develop a technique for hardening disposable bovie pens so that they can survive reuse. "	Electro-surgical pen having a removable cap that will reduce degradation of the pen. The removable cap will be designed to fit over the external tip of the surgical pen.	Stress analysis of tip for dropped pen and heat transfer analysis for effectiveness and safety were evaluated. Figure shows temperature profile in cap where surgeon would hold. 
Cold Box 	". . .A subset of substances are sometimes needed on very short notice, far from the refrigerator. . . .What is needed is a refrigerator of very small volume. It should be sufficient to store one days worth of the chemical. . . at about 10 degrees C for 12 hours.	Thermoelectric Cooling System for Cold Box	Top boundary condition is determined by thermoelectric cooling capacity. FEA was used to determine temperature profile where medicine would be stored when ambient temperature was high. Heat transfer by conduction and convection 
Infant Ventilator (CPAP) 	Many premature infants and underweight infants are born with insufficient levels of surfactants and . . . can suffer from a great deal of difficulty keeping their lungs inflated. . . . What is needed is a very small and portable ventilator capable of delivering CPAP (continuous positive airway pressure). . . "	Team designed a valve that would allow continuous positive pressure while allowing exhaled air to exit a separate port. This design allows positive pressure to be lower thus drawing less power.	Figure shows velocity profiles of air during exhalation when valve is closed. A closed valve has 70% resistance to allow continual positive pressure at mouth. 

Table 1. *continued*

Project title	**Web description**	**Design Concept**	**Engineering Principles involved**
Clorox Mixture Monitoring 	It is common to use free chlorine in water as a sterilizing agent in developing world hospitals . . . What is needed is a chemical or strip that can be added to water so that the water or strip changes color (or shape) to indicate that the amount of free chlorine is adequate for sterilization. . .”	Approach was to devise a mixing valve to assure that accurate proportions of water and chlorine are delivered at each use. This design prevents the need to store chlorine/ water mixture.	Analysis of streamlines and concentrations through mixing device was performed. 
Nebulizer 	The rates of asthma and pneumonia are very high in the developing world. . . .their access to appropriate medicine is hindered by the lack of robust nebulizers. . . aimed at using commercially available (in the developing world) air compressors and tubing to construct a robust, hospital grade nebulizer.”	Team designed a nebulizer for multipatient drug delivery.	Team analyzed fluid streams to support the idea that air flow would be sufficient to aid in vaporization of medicine at bottom of chamber. 
Transport Infant Incubator 	Worldwide, every year, over four million infants die within a month of birth. . . What is needed is a robust, low cost transport incubator . . . maintain the chamber at 37 degrees C. . . Prefer means to provide humidified air. Should operate during transport (battery or non-electric) and when in hospital”	Team developed a incubator that could be made of wood with a clear plastic top.	Team analyzed temperature distribution in incubator from heat source to test if target temperature is maintained where baby would lie. 

convection from the cold box and from the medicine.

In this example COMSOL was used to assess feasibility of design [text adapted from the team’s project report]. A dilemma in developing countries is the proper storage and delivery of medicine without access to a nearby refrigerator. For example, the drug used to contract the uterus after delivery, known as oxytocin, is unpredictably needed at short notice. Additionally, it is often needed in very remote areas to which it must be carried by hand. Without any access to refrigeration, the substance is often exposed to the heat for extended periods of time, and as a result, loses potency. This sort of transportation without refrigeration is the compromise that is made all too often due to lack of resources in developing areas. Few portable modes of refrigeration exist that are inexpensive and take advantage of alternative energy sources rather than depending on electricity for power.

The team designed a clay/straw box that would hold a 5mL vial of medicine. A simple kit would include a plastic mold in the shape of the outer box casing. This mold would be used to shape the clay and the mold could be used repeatedly at the manufacturing site. As insulating material, clay is inexpensive and easy to find. A COMSOL model was devised in which the thermal conductivity of clay was used and the initial internal temperature of the cold box was 10°C. A peltier cooling cap was designed to cover the cold box opening. With ambient temperature boundary conditions, and a heat flux boundary condition consistent with low power peltier cooling, results of a transient analysis showed that the medicine temperature would rise about 2 degrees (to 12°C) after 12 hours (see Fig. 2).

The ease of engineering application allowed

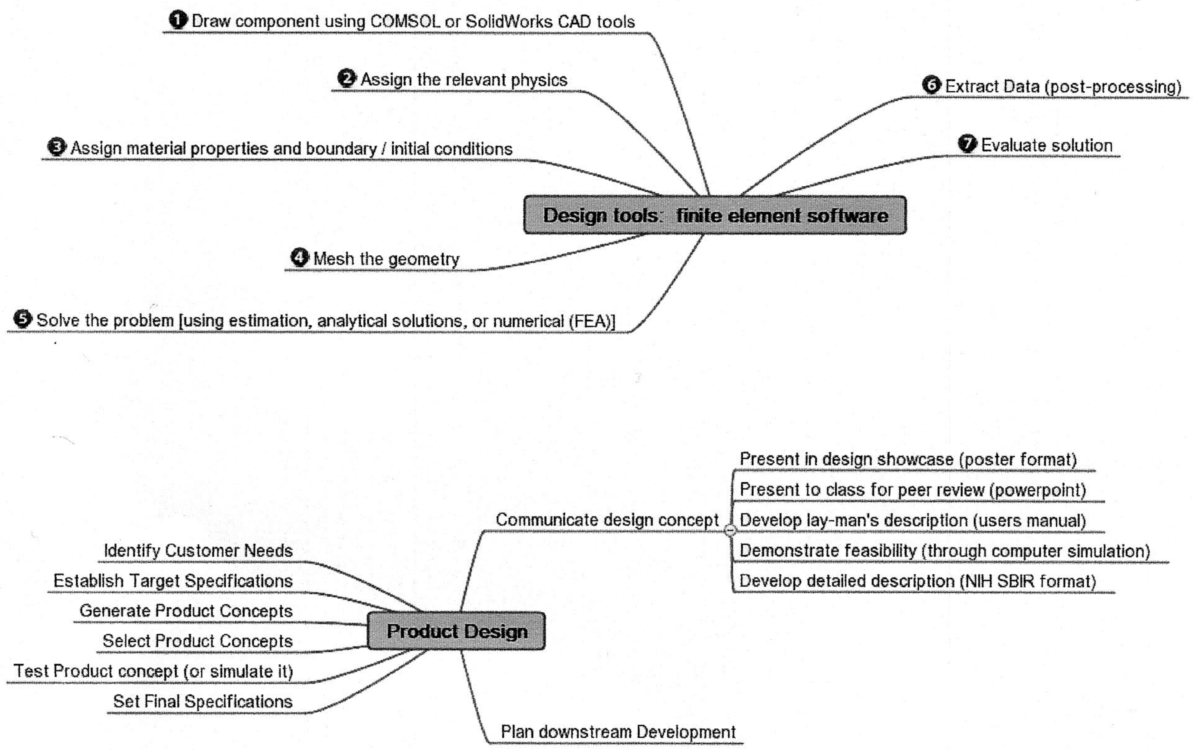


Fig. 1. Course learning objectives: mindmaps illustrate main learning objectives for integrating COMSOL multiphysics and product design.

Table 2. Integration of Design and COMSOL: finite element analysis principles were introduced in parallel with design strategies. "HE" is "humanitarian engineering"

Topic	Learning objectives	Integration of HE with COMSOL
Introductions and Course Overview	Intro to bioengineering design for the developing world	Identify Customer needs Establish target specifications Generate product concepts
Introduction to COMSOL Multiphysics	COMSOL Multiphysics overview / examples	Select product concepts
Drawing in COMSOL and Solidworks	COMSOL CAD Solid works CAD	Sketch design and components
Assigning the physics	Coefficient forms of PDEs in COMSOL / General conservation equations in COMSOL	Determine project-related physics
Fundamentals of FEA	FEA Overview Galerkin Method for PDE solution	Assign project-related minicourses
Meshing techniques / Solving in COMSOL	Meshing techniques in COMSOL Linear solvers / time-dependent / Non-linear solvers / iterative solvers	Perform mesh sensitivity analysis
Extracting data from FEA: post-processing	Post processing Data representation	Determine if design meets a critical specification through post-processing of model
Case study in Bioengineering Design using FEM / Applications of FEM to product design	Technological innovations in the developing world	Reiterate on design through parameterization of COMSOL model
Peer Review and Review by EWH	Students critique designs	Final report
Project showcase	Feedback from other HE faculty	Present design in poster format

students to focus on iterative design of the cold box materials and size as well as providing opportunity for more in-depth analysis of customer needs. The use of this humanitarian engineering design led to the need to simulate temperature changes in the medicine because the students would not have sufficient resources or time to build a prototype or to test it.

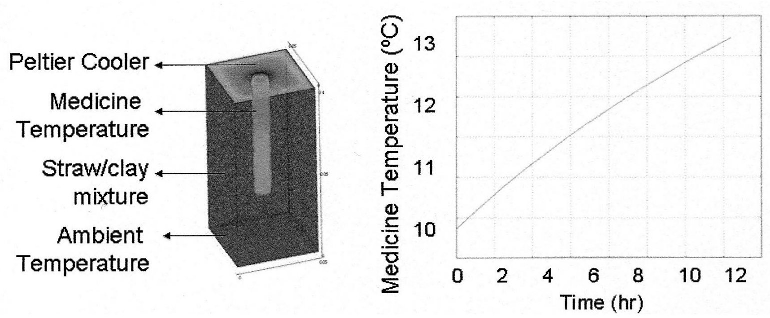


Fig. 2. COMSOL case study: cold box for medicine transport in hot environments was designed and heat transfer analysis was performed using COMSOL version 3.4 heat transfer module.

Table 3. Assessment of impact of humanitarian engineering (HE) on COMSOL integration into design curriculum: scores averaged and significance based on 95% confidence intervals. 27 respondents (75% of class enrollment) were averaged. Scores are based on (1) strongly agree, (2) agree, (3) disagree, (4) strongly disagree

Survey Question	**Score**	**Related Comments**
Use of Engineering for World Health design problems motivated me to learn finite element analysis software.	1.9 (Agree)	"The use of EWH designs was a great motivator. We were excited about designing something that could have a big impact on developing countries, and being able to analyze the real details of our design in COMSOL was a great experience. It was a great example of applying theory to a real-world setting. Using EWH was better than instructing students to just design something for the sake of learning the software, because it showed us that we can use bioengineering for applications other than just traditional medicine. It allowed us to think outside the box."
COMSOL Multiphysics software helped me see how I can apply my engineering knowledge to complicated geometries.	1.4 (Strongly Agree)	"The software was very effective in that, in many cases, a simple 2-D geometry could be used to analyze multiple characteristics of a possible design (i.e.—streamlines, gradients, flow vectors, etc). Specific to the infant incubator, if the temperature gradient of the initial design was not adequate, a simple alteration could be made until the gradient was sufficient. In addition, the effects of various materials could be analyzed by simply changing one parameter. This feature was the most favored as it allowed us to test what the best material would be for the design without having to construct multiple prototypes."
COMSOL multiphysics software helped me get simulated data that was useful in design iteration.	1.6 (Agree)	"Using COMSOL was absolutely the most concrete evidence we had for demonstrating the effectiveness of our design. Without COMSOL, it would have been difficult to demonstrate what our design accomplished."
The minicourses were useful for learning how COMSOL multiphysics works	1.7 (Agree)	"COMSOL Multiphysics is a very powerful program. It is capable of so many things that it can be overwhelming. At first it was difficult to understand even the most simple simulations, but with repeated minicourses and assignments with walkthroughs the program became less intimidating. These assignments were very helpful. "
It would be helpful if there were minicourses focused on the details of how COMSOL works such as meshing, solvers, post-processing, etc.	1.7 (Agree)	"The only things i would have to say I didn't like is that I found myself just going through the minicourses and following commands rather than taking in what I was actually doing. I think it would be helpful to have minicourses that did explain what each function was used for and a light overview on how it works."
My educational level was sufficient to use COMSOL multiphysics with confidence.	1.7 (Agree)	In order to complete the evaluation of the EWH designs, COMSOL was necessary. It allowed my group to actually calculate if the proper velocity and pressure were reached in order for effective medicine delivery.

ASSESSMENT

Peer review was accompanied by solicitations of comments from Robert Malkin, director of EWH [10]. Designs proved to be too preliminary to assess whether design solutions are usable by the customer. Future modification of the course will attempt to create prototypes and testing protocols.

Nevertheless, connecting design with EWH was helpful in showing the students that their designs would be considered for use.

We found that use of theme-based design courses, in general, provide a sustainable mechanism to introduce the integration of engineering and design (see Table 3). With themes, the faculty member in charge of the course can limit background information to that related to the theme and can quickly move into application of relevant engineering principles. In particular, the use of humanitarian engineering complements these learning objectives by providing open-ended design problems that motivate the students to use sophisticated computational tools.

Our survey results suggest that it may be useful to develop more targeted minicourses to teach some of the underlying principles of finite element analysis. For example, a minicourse that focuses exclusively on solution sensitivity to mesh density may be useful in addressing the issue of discretation in the Galerkin method. Nevertheless we have found that students agree or strongly agree with all statements asking if humanitarian engineering problems motivate them to learning COMSOL multiphysics finite element analysis software.

CONCLUSIONS

The expected impact of this paper is to encourage more streamlined integration of FEA into undergraduate education. At Penn State Bioengineering, there is little room for more courses in the curriculum, yet our industrial advisory board has emphasized the need for students to be able to tackle more ambitious and open-ended problems using advanced engineering analysis. Our approach of integrating FEA directly into design is a very deliberate one. FEA without applications makes it very difficult to motivate students to learn it. Design without engineering analysis reveals a fundamental disconnect between theoretical underpinnings of engineering and engineering applications. Our approach is to tackle these issues directly through problem-based design for real world problems using advanced engineering tools.

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