Product Design and Process Design in Chemical and Biological Engineering Capstone Courses

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This paper raises points of discussion related to the teaching of product design in chemical and biological engineering capstone design courses. Product design is emerging as an essential job function of our graduates to a degree not experienced by previous generations of chemical and biological engineers. This is accompanied by a waning of the significance of process design. Key constituencies such as ABET, future employers, and our student populations might all be satisfied by rigorous product design projects, if they are properly executed. However, product design projects may not satisfy the traditionally established criteria of chemical and biological engineering capstone design courses. As we reconcile these differences, chemical and biological engineering programs should be open to cues from other engineering disciplines, which have decades of experience in capstone design courses that teach product design, and should also consider input from partners in industrial practice who can help us define the skill sets that our graduating engineers require.

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Introduction

Traditionally, the pedagogical goals of the chemical engineering capstone senior design course have been clear, namely, to convey to the students the fundamentals of designing a continuous chemical/petroleum process, consisting of a grouping of unit operations, as well as the economics associated with such processes. During the 1980s the use of process simulators such as Aspen became an important method in accomplishing these generally agreed upon goals. Batch processing and product design, although central to the pharmaceutical, specialty chemical and other industries were generally not emphasized to the same extent.

However, over the last two decades, multiple trends in the chemical engineering discipline have produced challenges to this traditional approach. It is clear that the pace of construction in the US of continuous processes producing commodity chemicals has declined significantly in recent decades, and employment of chemical engineers in the traditional chemical industry has dropped below 20% of new graduates. The design future is no longer dominated by chemical and oil processing. In fact, it has been suggested that the future of chemical engineering for our students may involve much more *product* design than *process* design.[1] Indeed, our chemical and biological engineering graduates are increasingly involved in the design of products such as biomedical devices, biosensors, fuel cells, dialysis machines, etc. These projects require a different set of design principles that are probably less standardized than for process design. The capstone senior design experience has generally not kept pace with this shift in the discipline. Analysis and design of continuous processes remain the primary component of capstone design courses in chemical and biological engineering. Nevertheless, in order to best educate future graduates, any significant issues related to the transition to product design that is taking place should be clarified and resolved.

Teaching Product Design

The tools and approaches required to design a product do not necessarily overlap fully with those needed for the design of a continuous chemical process. Although the capstone course can include the teaching of both process design and product design,[2] concerns may arise when the senior design project itself involves only a product. An example is one of the recent senior design projects in the Department of Chemical and Biological Engineering at Colorado State University. One of our ambitious seniors, who planned to attend medical school, wanted to work on something related to biomedical engineering. She recruited a team of three other interested students along with a professor researching biomedical materials and proceeded to build, operate, and optimize an electrospinning device producing nanofibers of chitosan/poly(vinyl alcohol) blends. Surprisingly good results (given the time frame) were obtained with their equipment, which continues to be used in research in our department. Another one of our chemical and biological engineering seniors was recently part of a multidisciplinary team that designed and built a neonatal transport incubator. Colorado State University has plans in the future to offer a biomedical engineering undergraduate degree (to go along with its

MS and PhD programs). Seniors working towards this degree will eventually be engaged in the design and construction of a range of biomedical products like this one, on multi-disciplinary design teams.

The two senior design projects described above require a different toolkit than a student team would need to design a large continuous chemical plant. The question arises as to whether the electrospinning project or others in this vein, including product design, satisfy important constituencies such as employers and ABET. The feedback we have received at Colorado State University indicates some ambiguity and doubt surrounding this issue.

Satisfying Key Constituencies

ABET requirements for the capstone senior design course revolve around program criteria (a-k, Table 1), as well as the Continuous Improvement Criterion 4. Criterion 4 uses external evaluation of the design reports, internal and external evaluation of the final oral presentations, and student self-evaluation of team effectiveness, all employing ABET generated rubrics (Table 2).

Typically, a capstone senior design course and the embedded senior design project are expected, because of their comprehensive nature, to make a primary or secondary contribution to most, if not all, of the ABET program outcomes. Continuous chemical process design projects have satisfied the requirements of not only ABET but those of the American Institute of Chemical Engineers and the chemical industry for decades. Thus, an important question to ask is whether there is anything inherent in product design projects that would prevent them from doing the same. Looking at Tables 1 and 2, there do not seem to be any ABET criteria, outcomes, or requirements that could not be met by designing a product rather than a process. Consider the well-known example of a hemodialysis unit (the original design of which involved chemical engineers). There are no apparent deficiencies associated with this type of project. Similarly, the two examples described in the previous section involved all of the items in Tables 1and 2, to an extent comparable to a more traditional process design problem.

On the other hand, existing courses may be designed to focus on more specific topics not explicitly required by ABET. Such criteria might include the design of traditional unit operations (e.g., distillation), analysis of systems of unit operations with recycle, feedback control of steady-state processes, process scale-up, and environmental, health, and safety issues associated with high-temperature, high-pressure vessels containing large quantities of toxic or explosive chemicals. Product design projects may not meet these more specific requirements. Rather, each product design requires application of a unique set of design principles that may or may not be on the same list used for a process design.

Regarding another key constituency, the companies that hire graduating chemical and biological engineers, any lack of congruence between senior process and

Table 1. ABET program criteria

a. Ability to apply knowledge of math, engineering, and science
b. Ability to design and conduct experiments, analyze and interpret data
c. Ability to design system component or process to meet needs
d. Ability to function on multi-disciplinary teams
e. Ability to identify, formulate, and solve engineering problems
f. Understanding of professional and ethical responsibilities
g. Ability to communicate effectively
h. Broad education
i. Recognition of the need to engage in life-long learning
j. Knowledge of contemporary issues
k. Ability to use techniques, skills, and tools in engineering practice

Table 2. ABET report rubric components

1. INFORMATION GATHERING: Information identified and obtained to support design process and design decisions
2. PROBLEM DEFINITION: Development of design goals and specific requirements that will ensure a successful design
3. IDEA GENERATION: Gathering and creating new ideas and concepts for consideration in development of design
4. DESIGN QUALITY: Proper use of theory, equations, and engineering tools to develop design alternatives
5. EVALUATION: Using appropriate methods and tools to determine how well concepts meet requirements
6. CONSTRAINTS: Identification, evaluation, and incorporation of multiple constraints (e.g. safety, economics)
7. COMMUNICATION: Production of a design report that effectively communicates design process and results to client

product design projects may be of little concern. While degrees in chemical and biological engineering continue to represent expertise in chemical process design to potential employers, the spectrum of employers itself has shifted toward companies engaged in product creation and development rather than the design and operation of continuous chemical plants.

Finally, students represent a constituency that cannot be neglected as we consider how we teach any course. In our experience, product design projects have the potential to be much more student-driven. In both of the specific examples introduced above, the students have demonstrated an enthusiasm for defining and completing the project that is unparalleled by any recent process design projects. While students can be enthusiastic and intellectually satisfied by process design problems, they tend to be more motivated by product design projects. This could be because product design has the potential for building prototypes, whereas prototype building in a chemical process design project is considerably less likely or feasible. Students also tend to see product design as a more creative process. In both types of projects students must develop and apply heuristics, perform engineering design calculations, and optimize performance against multiple design criteria. Nonetheless, whether it is real or perceived, product design projects tend to contain an element of creativity to an extent that exceeds its presence in process design.

Suggested Points of Discussion

There should be little doubt that our chemical and biological engineering graduates are likely to be equally if not more involved in product design than in process design throughout their careers. Nonetheless, process design is and will remain a fundamental core discipline of chemical engineering education and practice. Recognizing that these two pursuits may require different skill sets, chemical and biological engineering educators should consider how product design might be incorporated more seamlessly into our existing curriculum, and the senior capstone design experience is a logical place. Chemical and biological engineering programs should take advantage of the decades of experience that our colleagues in other engineering disciplines have gained to develop pedagogies for teaching product design, and should look to practicing chemical and biological engineers in industry for guidance as to the skill sets that our future graduates will require. To that end, the recent edition of the text by Seider, Seader, Lewin, and Widagdo incorporates product design principles with more traditional chemical process engineering.[2]

References

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2. W.D. Seider, J.D. Seader, D.R. Lewin, S. Widagdo, *Product and Process Design Principles: Synthesis, Analysis, and Evaluation* (John Wiley and Sons, Hoboken, NJ, 3rd ed., 2009).