Redesigning Senior Process Design

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Introduction

Senior design is widely regarded as an important capstone experience for undergraduate engineering students. By integrating material from previous courses, it provides a conceptual framework for tackling a wide variety of open-ended, real-world engineering problems. Traditionally, senior design consists of the following common elements: process economics, capital costing, simulation and a grass-roots design project. As the nature of the chemical engineering profession has evolved and expanded into new areas, there has been increasing pressure to modify senior process design to better prepare graduates for the realities which they will face during their careers. Some of the challenges discussed in the literature include the following:

1. Shifting the emphasis from process design to product design within the chemical industry [1-3].
2. Including the design of batch processes in addition to continuous processes to reflect the growth areas of the chemical industry [4].
3. The need to understand the business factors that affect design [3,5]
4. The need to incorporate sustainable development and design of green processes [6].

In addition to changes in the engineering profession, several educational challenges must be addressed to allow senior design to provide the benefits that are desired. These challenges include the following:

5. Students are often uncomfortable with open-ended problems with no single right answer. Because these types of problems typically occur primarily in senior design, they have limited opportunity to learn how to approach them [7].
6. The design project was traditionally assigned during the latter part of the spring term of the senior year. Students often lack time and energy to wrestle with the difficult, open-ended issues and have difficulty pursuing the project to a sufficient depth.
7. Because design occurs at the end of the curriculum, it is difficult to offer electives that would build on the design material.

Over the past several years, the senior design sequence at Rose-Hulman Institute of Technology has been redesigned to address many of these seven challenges. We have expanded the design sequence from 8 credit hours over 2 quarters, to 10 credits over 3 quarters to allow the inclusion of additional material as well as increased time to work on open-ended projects. This paper discusses the new senior process design sequence in detail, the trade-offs considered during its redesign, the rationale for the changes, and outcomes that have been observed to date.

Course organization

The core focus of our design sequence is help the students learn to approach open-ended problems rationally and with confidence in order to comprehensively address challenge 5. To this end, we have structured the 3 courses to provide the students not only with the tools they need for analysis, but also with multiple opportunities to apply those tools to open-ended, ill-defined problems. The first course focuses on the design of individual pieces of equipment through the use of both simulation and heuristics. The second course builds on this foundation by incorporating rigorous profitability measures with systems level tools for process analysis and improvement. The final course requires students to integrate their knowledge to be able to complete a grass-roots design project. The first two courses use the "Product and Process Design Principles" textbook [8]. All three courses also require extensive use of reference materials, such as handbooks, journal articles and patents. Details of the contents and the underlying rationale are described below.

CHE 416 Design I: Process Economics and Equipment Design

The first course focuses primarily on the design of single pieces of equipment and small systems through the use of both simulation and heuristics. A significant effort is placed on demystifying process simulation by helping the students to understand the inner workings of a simulator so that they recognize it as just a tool, similar to a calculator. The topics and organization are listed in Table 1.

In the center of the learning activity is the development of the cognitive skills at the highest level (synthesis and evaluation) by building on the lower level skills (knowledge, comprehension, application and analysis) that have already been fostered during the first three years of the curriculum. Table 1 summarizes the topics covered in the course. Each topic starts with material already covered elsewhere in the curriculum and gradually increases the cognitive challenge through in-class discussions, examples and homework assignments. The key is to provide students with material that emphasizes achievement and creativity rather than just understanding and repetition. For example, students are asked to carry out a detailed design for a distillation column, including the condenser, the reboiler, the accumulator and the associated pumps; to evaluate process alternatives for a reactor-separator-recycle network; to synthesize a separation train.

An important goal of the course is the application of heuristic rules to generate or eliminate design alternatives. Heuristics are based on relatively simple rules of thumb. They are easy to understand and provide a framework for workable designs. Special attention is placed on the decision-making process when heuristic rules contradict each other. These situations are perfect examples of the open-ended nature of design and provide opportunities for the students to engage in high level cognitive activity, such as synthesis and evaluation.

A significant portion of the course is dedicated to process simulation. The routine use of process simulators in industry dictates that chemical engineering graduates should be competent to apply these tools in the analysis, synthesis and evaluation of process designs. At Rose-Hulman Institute of Technology chemical engineering students are introduced to process simulators in their sophomore year and use them on a limited scale in most of the required chemical engineering courses. The objective in this course is to ensure that simulation enhances student understanding of the physical process, rather than simply generating numbers. The inner workings of steady-state flowsheet simulators are discussed throughout the course and the pitfalls created by incompetent use of the simulators are repeatedly emphasized.

The final two weeks of the course are spent on capital cost estimation. This provides a link into the following class, where more detailed economic analysis and business decision making are introduced. Capital cost is estimated through graphs, equations and cost indexes as well as through the use of computer programs, such as Aspen IPE.

CHE 417 Design II: Process Synthesis and Analysis

The second course focuses on tools that can be applied to larger systems. The topics and organization of the course are listed in Table 2.

As the focus moves from individual equipment to entire processes, the students are first introduced to the economic analysis tools appropriate for large-scale projects. In the course of this discussion, the students are introduced to the idea of the uncertainty associated with predicted prices and demands and gain an understanding of the need to understand market conditions when planning to introduce a new product, addressing challenge 3. Students will have additional opportunity to make use of business decision making concepts during CHE 418.

Table 1. Course topics for CHE 416 – Design I.

	Topic	**Class Periods**	**Simulation Tool**
1	Preliminary Process Synthesis	2	
2	Principles of Steady-State Flowsheet Simulation	2	Aspen Plus
3	Separation Trains Heuristics	2	
4	Distillation Column Heuristics	2	
5	Distillation Column Design	3	Aspen Plus
6	Heat Exchanger Heuristics	2	
7	Shell-and-Tube Heat Exchanger Design	3	Aspen Hetran
8	Air-Cooled Heat Exchanger Design	3	Aspen Aerotran
9	Reactor Design Heuristics	2	
10	Reactor – Separator – Recycle Heuristics	2	
11	Reactor – Separator – Recycle Design	3	Aspen Plus
12	Pumps, Compressors and Expanders Design	2	Aspen Plus
13	Capital Cost Estimation	7	Aspen IPE
	Total class periods	**35**	

The next major tool introduced in the class is approaches for optimization. Students learn not only why optimization is important, but also work a variety of problems to understand the practical significance of optimization results. The optimization tools used in the course range from Excel (which, although the least powerful, will be accessible to nearly all the students after graduation) to Aspen Plus and GAMS. This introduction at the lower cognitive level is then built upon in subsequent course material as they move toward synthesis and evaluation.

These optimization techniques, along with the economic analysis tools, are then applied when learning about molecular design, heat and mass integration, and batch process design. Molecular design provides a relevant problem for introducing ideas related to product design (challenge 1) while also allowing aspects of green engineering and sustainable development (challenge 4) to be incorporated into the selection of a molecular entity. Those students particularly interested in these ideas can pursue them further during their third quarter project.

Heat and mass integration help the students better understand the systems level interactions in a process as well as providing a framework for analyzing and improving processes. Students are expected to apply these tools in their project work as appropriate. Finally, a module on batch design process addresses challenge 3 and lays the groundwork for interested students to further pursue a grassroots project in this area.

Concurrently, the students are working on a large, open-ended process improvement project. The project begins as an exercise to review capital costing methods from the previous course and integrate that with economic analysis. The students are then informed that based on their recommendation, the plant has been built, and they should investigate how the process could be improved. Different prices for the raw materials, products and utilities are provided to simulate the effect of the passage of time. The students approach the improvement project using tools based on process diagnostic summaries to identify improvement opportunities [8]. They can also apply heat and mass integration, since that is being discussed in class while they are working on the project.

Table 2. Course topics for CHE 417 – Design II.

	Topic	**Class Periods**
1	Process Economics And Profitability	8
2	Business and Marketing Factors Affecting Design	3
3	Optimization	7
4	Molecular Design (Product Design)	2
5	Heat Integration (with optimization)	7
6	Mass Integration (with optimization)	4
7	Batch Process Design	5
	Total class periods	**36**

At the end of this course, students are sufficiently prepared to take advanced elective offering in the design area, addressing challenge 7. Although we have not currently begun offering advanced design electives, we hope to do so in the coming years.

CHE 418 Design III: Capstone Design Project

The third course, CHE418, gives the students an opportunity to pursue an open-ended grass roots design project. Since this is now a full 10 week course, challenge 6 has been addressed, so that the students have twice as long to complete their project. (Previously, fewer topics were incorporated into Design 1 & 2, with the final 5 weeks of Design 2 set aside for a single design project.)

With the additional time available for the design project, students are expected to begin their project with a market survey of their product area. This includes identifying prices and suppliers of raw materials, potential processing methods, current and planned production capacity and competitors in the market space. Most projects have focused on process design; however, the range and types of projects have been quite diverse as shown in Table 3. Thus, students have an opportunity to pursue projects that make use of traditional continuous processing, batch processing and bioprocessing. In addition, students have the opportunity to pursue product design projects where they start with a product requirement instead of a desired molecular entity. It is within the final project that students are given the most direct opportunity to design green processes (challenge #4).

Table 3. List of recent final design project descriptions.

	Final Design Projects
1	A pain reliever (Aspirin and Ibuprofen have been the resulting compound)
2	Acetic acid
3	AIChE Contest Problem
4	Apoaequorin (a protein) to be produced via fermentation/purification process.
5	Aspartame (an artificial sweetener)
6	Clean coal process for electricity generation
7	Coelenterazine, a high value fine chemical used as a substrate for luciferase and other photon producing proteins.
8	Florfenicol (a synthetic bovine antibiotic)
9	Fluoxetine (a pharmaceutical product)
10	Isopropylamine salt of glyphosate, N-(phosphonomethyl)glycine (the active ingredient in Roundup herbicide)
11	Isopropylthiogalactoside (IPTG), which is widely used in the modern fermentation industry.
12	Maleic Anhydride
13	Penicillin V
14	Polyethylene (HDPE)
15	ZYRTEC® (cetirizine hydrochloride) an antihistamine pharmaceutical

All the students benefit from this diverse range of design projects. They get to pursue projects in their areas of interest, sharpening their skills in these areas. In addition, they get to learn from one another when each group presents not only their final design, but also their design process, to the entire class at the end of the quarter.

Student demographics and response

Almost all students that are enrolled in the Chemical Engineering program at Rose-Hulman Institute of Technology have entered college immediately upon graduating from high school. The majority of them have come directly to Rose-Hulman Institute of Technology. Less than 5 % have transferred from other universities. By the beginning of the senior year most students have had a practical experience in Chemical Engineering through coop or summer internship programs. Table 4 shows the total enrolment and the gender distribution in the senior process design classes in the past two academic years.

Table 4. Total enrolment and the gender distribution in the senior process design classes in the past two academic years.

	ChE 416 – Design I		**ChE 417 – Design II**		**ChE 418 – Design III**	
	AY 03-04	**AY 04-05**	**AY 03-04**	**AY 04-05**	**AY 03-04**	**AY 04-05**
Enrolment	60	49	57	51	55	51
% Male	72	45	70	47	69	47
% Female	28	55	30	53	31	53

Students have generally responded favorably to the changes in the design sequence. Comments have included the following (arranged by course). CHE 416 and CHE 417 have now been offered twice in its current form allowing for additional feedback to be presented. Assessment of the changes is ongoing, and we hope to present more quantitative data in the future.

CHE 416 Design I: Process Economics and Equipment Design

- I learned skills that will be useful towards problem solving upon graduating.
- I learned a lot about what things to considering and what things are unimportant when designing equipment for engineering applications.
- The course ties in a lot of the material we covered in other courses. It was not so much a review as it was how to combine the different course material into one big process.
- This class gave a lot of good information, using all of the past three years of classes and putting them all together.
- This course was challenging because it combined a lot of knowledge from other classes with new information.
- Most of the things we learned were supposed to be review, but we went in greater depth and actually made designs.

- Extraordinary integration of what we've learned in thermo, heat transfer, mass transfer, kinetics, etc...mostly superb use of technology in Hetran, Aerotran, Aspen Plus, IPE, etc...excellent coverage of material...

CHE 417 Design II: Process Synthesis and Analysis

- Enjoyed this course quite a bit. A lot of that has to do with my personal intellectual satisfaction when getting to apply several different parts of my course studies and solve open-ended problems successfully.
- The topics covered in this class were very interesting, and very relevant to process engineering.
- Just enough homework to get the job done, and to iterate the right ideas without going overboard.
- Working with different computer programs was helpful. Being exposed to optimization in three different programs provided us with more options in solving those type of problems.
- The project did a nice job bringing a lot of concepts I learned together.
- The project allowed for application of the concepts, and the learning material was directly applicable to real-world situations.
- A broad spectrum of topics was covered giving an overall set of tools which many of us will use as we enter our careers.
- It's real world applicable.... at least I think it is....
- I feel like I gained a lot of practical knowledge from this course, as it pulled everything together. I actually enjoyed what we were doing for the project.
- A good balance of old material applied to new concepts.
- It allowed me to learn many more skills that i will use after school is out. I felt like I could really use everything that we learned on the job.
- It is good to finally be pulling together the concepts we have learned.
- Even though the group project was time consuming, I really think that it was a good way to combine many of the concepts which we learned in this class. Good!
- It ties together a lot of stuff to help us prepare for the real world.

CHE 418 Design III: Capstone Design Project

- Having the whole quarter dedicated to the project worked out well. It gave us the opportunity to work on the project more effectively and to work it into our schedules.
- The class part of design 2 helped as far as the economic stuff goes. As far as coming up with our own material balances from scratch, I don't think we were prepared for it. But it wasn't as hard as I thought it would be after design 1 and 2.
- The idea of our own "grass roots" project and developing the entire design and cost analysis in a small team is an incredible idea as an exit course for seniors.
- The design procedure seemed to be beneficial. I was able to get first hand experience in what it takes to design a process.

Conclusions

In conclusion, our redesigned Senior Design Sequence has allowed us to address seven major challenges facing chemical engineering education. Students obtain a sufficient introduction to product design and batch process design that they can pursue a final design project in this area (challenges 1 & 2). They learn about the business factors that affect design (challenge 3) and have to address these as part of their final design project. Through a number of assignments and projects that are increasingly open-ended, student learn how to approach ill-defined, open-ended problems with greater confidence (challenge 5). Challenges 6 and 7 are addressed by making the final project a course in itself in the spring quarter, allowing for an advanced design elective to be offered at the same time. Challenge 4 is currently most directly addressed during the final design project for those groups that choose to pursue a project related to green engineering or sustainable development.

References

1. E.L. Cussler & G.D. Moggridge, *Chemical Product Design*, Cambridge University Press, 2001.
2. G. Stephanopoulos, *Invention and Innovation in a Product-Centered Chemical Industry*, A webcast lecture sponsored by CAST division of AIChE, October 26, 2004.
3. W.D. Seider, J.D. Seader, D.R. Lewin, "PSE and Business Decision-Making in the Chemical Engineering Curriculum", In Process Systems Engineering 2003 (Proceeding of 8th International Symposium on Process Systems Engineering, KunMing, China) B. Chen and A.W. Westerberg, Eds. Elsevier (2003) 74-87.
4. S.E. Mancini, "Chemical Engineering in Process Development and Manufacturing of Pharmaceuticals", Part of *Industrial Panel on Industrial Needs from CHEG Graduates*, ChE Summer School, Boulder, CO, July 29, 2002.
5. R. E. Sandström, "Industrial Needs from CHE Graduates", Part of Industrial Panel on Industrial Needs from CHEG Graduates, ChE Summer School, Boulder, CO, July 29, 2002.
6. D.T. Allen & D.R. Shonnard. *Green Engineering: Environmentally Conscious Design of Chemical Processes*, Prentice Hall, 2001.
7. P.C. Wankat & F.S. Oreovicz. *Teaching Engineering*, McGraw-Hill. 1992.
8. W.D. Seider, J.D. Seader, D.R. Lewin, *Product and Process Design Principles*, Wiley, 2004
9. D.C. Miller, T.N. Rogers and B.A. Barna, "An introduction to process simulation for the capstone design course'" In *Proceedings of the 2001 ASEE Annual Conference*, Albuquerque, NM. 2001.

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