LEHIGH DESIGN COURSE

Vincent G. Grassi, William L. Luyben and Cesar A. Silebi
Lehigh University • Bethlehem, PA 18015

The traditional senior capstone design course has been an integral part of the chemical engineering curriculum for many decades. A recent paper by Biegler, et al.,[1] discusses the importance, history, and trends. The course is usually a single semester and covers only steady-state aspects of process synthesis (flowsheets, economics, and optimization).

The desirability of combining steady-state and dynamic design has been discussed in process design circles since the pioneering work of Page Buckley at DuPont in the 1950s. Papers and books have been written. Talks have been presented. Symposia have been run. The advantages of coupling design and control have been clearly identified. The simulation tools (software and hardware) are available. Design and control methodology has been developed and documented.

It appears, however, that little of this "theology" has been implemented in chemical engineering senior design courses. In almost all chemical engineering departments, process designs are developed with little or no consideration of whether or not the process is controllable. In our opinion, this represents a major flaw in the education of chemical engineers. Old war stories abound of multi-million-dollar plants that have been built but could never be economically and safely operated because of dynamic instabilities. The senior author of this paper has taught process control courses at Lehigh University for many years. Up until two decades ago, his research was in the area of process control of individual units (distillation columns and reactors) and control structures and tuning issues. He was not involved in teaching the senior design course, which was taught by faculty with strong engineering backgrounds (Alan Foust, Leonard Wenzel, Matt Riley, Marvin Charles, and Harvey Stenger). In the mid 1990s the research began to consider broader plantwide control issues in collaborative work with Bjorn D. Tyreus and Michael L. Luyben of DuPont.

The need to incorporate this technology into the Lehigh design course was argued at faculty meetings. As usual, the result was "If you think it is a good idea, you have the job of doing it!" For several years we struggled to shoehorn the material into our one-semester design course. Finally the faculty recognized the importance of the subject, and our curriculum was modified in 1995 to include a two-semester design course.

Many of our ideas for the design course came from productive contacts with Warren Seider at the University of Pennsylvania, who has used industrial consultants in his design course for many years. He was the source of many industrial contacts and suggestions for design projects.

We recognized that design, optimization, and control were subjects that needed to be included in design courses. Chris Floudas at Princeton shared this view. To follow up on these ideas and develop the technology, NSF funding was obtained for Penn, Princeton, and Lehigh in 1996. Funds were used for computer-aided classrooms and courseware development.

The scope of the Lehigh design course and its format have remained essentially the same during the subsequent decade. The course format works well as evidenced by the fact that essentially all of the student groups are able to complete the process design and plantwide control of complex chemical plant processes using a commercial

Vince Grassi *is the director of Global Learning at Air Products and an adjunct professor of chemical engineering at Lehigh University. Vince has more than 32 years of engineering, management, and global business industrial experience. He has a BS from the University of Rochester, and M.S. and Ph.D. degrees form Lehigh University, all in chemical engineering.*

William L. Luyben *is a professor of chemical engineering at Lehigh University. He received his B.S. from Penn State and Ph.D. from the University of Delaware. He teaches Unit Operations Laboratory, Process Control, and Plant Design courses. His research interests include process design and control, distillation, and energy processes.*

Cesar A. Silebi *is a professor of chemical engineering at Lehigh University. He received his B.S. from Universidad del Atlantico in Colombia and his Ph.D. from Lehigh University. He teaches Heat Transfer, Mass Transfer, and Process Design courses. His research interests include electrokinetic and hydrodynamic fractionation of colloids and rheology of dispersions.*

grade process simulator. The industrial consultants serve to validate the quality of the work product. These are discussed in the following sections.

FORMAT

Groups of not-more-than three students are formed at the beginning of the fall semester. There are many methods for selecting groups, but we believe the completely random "volleyball" method is fair and effective (line up students by height and count off by the number of groups to be formed). Group dynamics are an important element of the course, which the students do not experience in any other course.

TABLE 1
Present and Past Industrial Consultants

Art Abriss	Sun Oil, retired
Don Bartusiak	Exxon-Mobil
Paul Belanger	Praxair
Jim Case	Air Products
Allan Cheung	Exxon-Mobil, retired
Brad Cook	Air Products
Bert Diemer	DuPont
Glenn Dissinger	Aspen Tech
Mike Dou	Exxon-Mobil
Ted Fidkowski	Air Products
Vince Grassi	Air Products
F. Glen Gallagher	DuPont
Tom Hanson	Praxair
Dennis Hendershot	Rohm&Haas, retired
Keith Holtermann	Air Products
Miles Julian	DuPont, retired
Gary Kohler	Exxon-Mobil, retired
Glenn Kinard	Air Products, retired
Ed Longwell	DuPont
Gene A. Lucadamo	Air Products, retired
Bryon Maner	Air Products
Larry Megan	Praxair
Bob Moore	Air Products, retired
Ron Myers	Rohm&Haas, retired
Frank Petrocelli	Air Products
John M. Repasky	Air Products
Dave Prior	Air Products
Dave Short	DuPont, retired
Walt Silowka	Air Products
Oliver Smith	Air Products
Bjorn Tyreus	DuPont

Each group meets with an industrial consultant who has generated a brief write-up of the design project. The students and the consultant use primarily e-mail and net-meeting to stay in contact during the year. Table 1 lists past and present consultants.

The course uses team teaching with two Lehigh faculty and an adjunct professor with extensive industrial experience in both process design and process control. All of the faculty are knowledgeable in both steady-state and dynamic simulation.

TABLE 2
Schedule Fall and Spring Semesters

Week	Recitation Topic	Lecture Topic
Fall		
1	Organization, Group Selection	Design Fundamentals
2	Introduction to AspenPlus	Consultant Presentations
3	Reactors in AspenPlus	Reactor Design
4	Columns in AspenPlus	Distillation Design
5	**Progress Report No. 1**	
6	Recycle in AspenPlus	Energy Systems
7	Ternary Diag., Azeotropes	Azeotropic Distillation
8	Group Meetings	Economics
9	Group Meetings	Economics
10	Group Meetings	Project Leadership
11	**Progress Report No. 2**	
12	Group Meetings	
13	Group Meetings	
14	Group Meetings	
	First-Semester Written Report	
Week	**Recitation Topic**	**Lecture Topic**
Spring		
1	Intro to Aspen Dynamics	Control Basics
2	Columns in Aspen Dynamics	Distillation Control
3	Reactors in Aspen Dynamics	Reactor Control
4	Recycles, Ratio, Flowsheet Eqn.	Plantwide Control
5	**Progress Report 1**	
6	Group Meetings	Process Safety
7	Group Meetings	Process Safety
8	Group Meetings	Equipment Safety
9	**Progress Report No. 2**	
10	Group Meetings	Human Factors
11	Group Meetings	Sustainability
12	Group Meetings	
13	Group Meetings	
14	Group Meetings	
All-Day Oral Presentation of Design Projects to Consultants and Faculty **Final Written Report Covering Both Semesters**		

Team teaching provides a spectrum of perspectives and technical expertise that enhances the learning experience of the students.

Lectures are presented that give the students the principles and guidance they need to complete their projects. Recitation sessions are held to provide hands-on experience with the Aspen simulations in a laboratory environment. The students are coached in the recitations on how to use the simulators, what to look out for, and how to analyze the results. Table 2 gives the course syllabus for the fall and spring semesters.

Homework assignments are given early on in the course so that the students can apply what they have learned in the lectures and recitations. This helps them understand the material and makes their work on their projects more productive.

Oral progress reports are given by the students twice during each semester. At the end of the spring semester, an all-day meeting is held with consultants at which the students present their final results. Written reports are submitted at the end of each semester.

Regularly scheduled, frequent "one-on-one" meetings are held with the faculty and each individual group to review progress, answer questions, and provide technical assistance.

Guest lecturers from industry with extensive expertise in special areas are used to cover several important topics. Miles Julian gives several lectures covering practical engineering economics and provides a spreadsheet to facilitate economic analysis. Dennis Hendershot and Bob Rosen give excellent lectures in their area of expertise, process safety.

The emphasis on process safety is essentially the only exposure to safety our students receive. Quantitative studies of dynamic reactor runaways and vessel over-pressuring can be made with the dynamic simulations of the process equipment. This safety analysis component of the process is a major advantage of incorporating dynamic simulation in the design course.

SCOPE

The two-semester course covers the traditional capstone design course topics plus dynamic plantwide control. The subject matter is summarized below.

1. *Introduction to Process Synthesis and Analysis – flowsheets, material and energy balances, reaction and separation sections, recycle, energy systems (steam, power, and refrigeration)*
2. *Distillation Column Synthesis – alternative sequences, pressure selection, reflux ratio/number of trays trade-off, column sizing, and auxiliaries.*
3. *Reaction Systems – alternative types of reactors, getting kinetics from performance data, importance of heat transfer, recycle/size trade-off*
4. *Engineering Economics – sizing, equipment and operating costs, profitability*
5. *Design Optimization – degrees of freedom, design optimization variables, heuristics*
6. *Process Safety – fundamentals of explosions, inherently safer design, case studies, relief-valve design, dynamic runaway of reactive systems, dust explosions*
7. *Dynamic Controllability – control of individual units, plantwide control, controller tuning, management of fresh feeds.*
8. *In-depth practice with Aspen Plus and Aspen Dynamics covering the use of these industrial grade simulators for plantwide processes with separation, reaction, and recycle.*

TYPICAL PROJECTS

There are 12 to 15 separate projects each year. Several recent projects are listed below.

1. Hydrotreating for the production of low-sulfur diesel
2. Isomerization of n-butane
3. Refinery light-ends
4. Carbonylation of DME to produce methyl acetate
5. Conversion of methyl acetate to acidic acid
6. Production of DME from methanol
7. Production of MTBE
8. Combustion turbine with CO_2 recovery
9. Steam methane reforming to produce H_2
10. Production of monoisopropyl amine
11. Alkylation of C4 olefins
12. Production of dimethyl acetamide
13. Production of ethyl lactate
14. Drying distillers dry grain using DME
15. Ethanol from ethylene
16. Coal gasification for syn gas production
17. Syn gas to methanol
18. Production of ethylene oxide
19. Production of butyl acetate
20. Production of ethyl benzene
21. Production of styrene
22. Liquid hydrogen

STUDENT COMMENTS

1. *So far the CHE 234 design course has been very beneficial for my understanding of process design and control and crucial to understanding and completing my design project.*

2. *I have learned that I need to fully understand the objectives and scope of the problem to be solved before using Aspen. This saves me a lot of time to diagnose a process problem from a use of the simulator problem.*
3. *The homework and recitations are very helpful. They allow me practice applying the principles of process design before I tackle the more difficult project problem.*
4. *Aspen is very powerful and complex. I have learned that one small mistake in coding Aspen can lead to many hours fixing it. Therefore I have learned it is essential to understand how the simulator works and could be applied to my specific problem before entering it into Aspen.*
5. *The project has taught me a lot more than I expected. I have a better understanding how systems thinking must be applied to process design.*
6. *My team learned how team communication is important. We need to coordinate how we divide up the problem, rather than just assigning a section to each team member.*

DESIGN/CONTROL EXAMPLE

It might be useful to present a simple example of the design/control issues that are core of the Lehigh design course. Consider the two alternative flowsheets shown in Figure 1. The chemistry is A → B. Component A is more volatile than component B, so any unreacted A goes overhead in the distillation column and is recycled back to the reactor.

The process on the left features a moderately sized reactor, so the conversion is somewhat low. A fairly large distillation column is required to recycle the reactant. Reactor size is given in gallons.

The process on the right is designed for higher conversion, so a bigger reactor is required. The column is smaller.

An economic analysis reveals that the total annual cost of the flowsheet on the left is smaller than that of the flowsheet on the right. Total annual cost includes energy cost and annual capital cost.

So which process should be built? The Lehigh answer to this question is ***"We do not know!"***

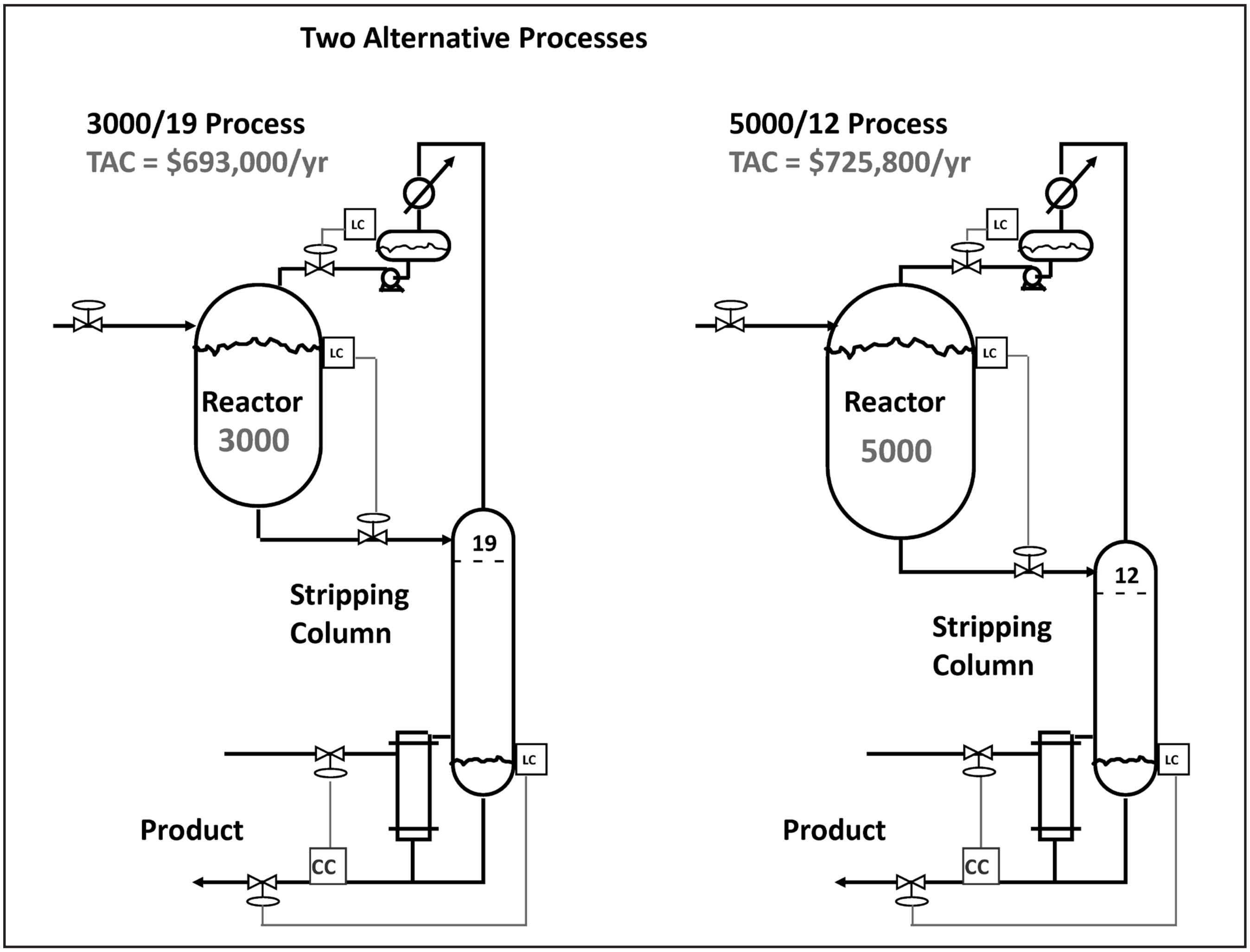

Figure 1. *Alternative processes.*

Until dynamic controllability is assessed, we do not know which flowsheet is "best."

The results of dynamic testing of the two processes are shown in Figure 2. The plant with the smaller reactor shows much more product quality variability as disturbances enter the system. The larger reactor does a better job of filtering these disturbances.

"On-aim" control is assumed, so anytime the product impurity is outside the control band production during these periods represents a cost. The product must be reworked, sold for less, or disposed of. The capacity factor is defined as the fraction of the time that on-spec product is being produced.

The small-reactor process is out-of-spec 29% of the time. The large-reactor process is only out-of-spec 7% of the time. The size of the equipment must also be increased to produce the required net production rate. The net effect is that the profit of the small-reactor process is about half that of the large-reactor process. Remember that the steady-state economic criterion of total annual cost showed that the small-reactor process was less expensive.

This example illustrates one practical approach to the issue of how to balance steady-state economics with dynamic operability, which is discussed in the course. The capacity factor method looks at both TAC (total annual cost of energy and capital) and the economic results of making off-spec product (larger plant needed to achieve required production rate and cost of handling the off-spec material).

CONCLUSION

The incorporation of dynamics into the plant design course is essential in the education of our chemical engineering students. Covering only steady-state design is studying only half the problem. The Lehigh design course illustrates one way to satisfy this need.

REQUIRED TEXTBOOKS

1. Luyben, William, *Distillation Design and Control Using Aspen Simulation*, AIChE, Wiley-Interscience, 2006
2. Turton, Richard, et. al, *Analysis, Synthesis, and Design of Chemical Processes*, 2nd Ed., Prentice Hall, 2003

REFERENCE

1. Biegler, L.T., I.E. Grossmann, and A.W. Westerberg, "Issues and Trends in the Teaching of Process and Product Design" *AIChE Journal*, **56**, 1120-1125 (2010) ❒

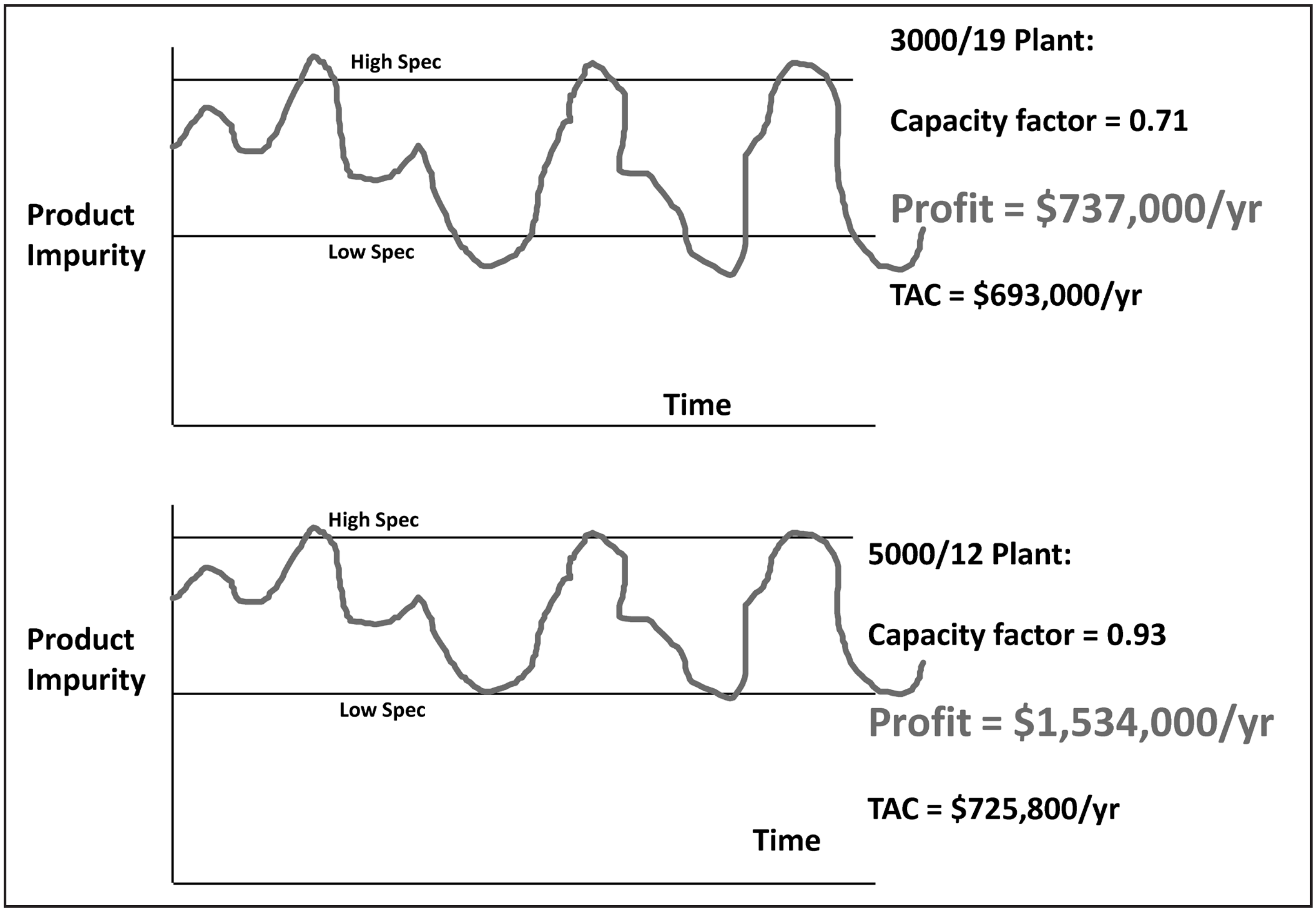

Figure 2. *Load responses.*