

Teaching Process Design – Quo Vadis?

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Abstract

The capstone course in chemical process design, together with its associated design project is the acid test to gauge the mastery of trainee chemical engineers. There is no other component in the chemical engineering curriculum that performs this function to this degree. This paper presents the results of an international survey to investigate the current teaching practices with regards to instruction in chemical process design. The results indicate that virtually all capstone courses have substantial group-based design projects. Process simulation is used extensively, while the targeted technical skills are often still classical design and economic evaluation techniques. Heat integration is also very highly considered (94% of respondents) perhaps reflecting awareness of global energy issues. Interestingly, the way teaching session time is distributed between activities (e.g. lecturing versus active learning techniques) falls into a clear bimodal distribution, reflecting distinct teaching philosophies and styles.

Keywords: Capstone design, Process design instruction, Design project, Active learning.

1. Introduction

“The design course will become even more important given the challenges posed by increasing relevance of designing sustainable process and energy systems. Chemical Engineering as a discipline should recognize this fact and not treat process design a second-class course as is done by a number of universities.” *Ignacio Grossmann, CMU*

Process design is a core component of chemical and biochemical engineering education. In most universities and institutions, the process design course either involves or is followed by an extensive design project. The design project is often considered a core activity in the education of future chemical engineers because it develops their skills in creative, innovative, and critical thinking beyond the boundaries of their acquired knowledge, as well as in collaboration in a team. It also integrates the various technical topics into a single project, evidencing the interdependence between classes that are usually taught separately and leading the students to acquire a general overview of chemical engineering activities. Such skills are likely to be crucial to empower students

to develop process technologies that respond to the relevant future challenges in process design and/or of the world. These future challenges include accommodating alternative raw materials and energy resources, alternative or more flexible production schedules, engineering ethics, health and safety and addressing sustainability concerns (Lewin and Zondervan, 2022) including UN sustainable development goals. Some schools already integrate certain of these challenges in process design courses and design projects, e.g., water and energy conservation as well as CO₂ capture, storage and utilization, and biologics manufacturing (El-Halwagi, 2017; Osman et al., 2020; Léonard et al., 2017). At the same time, process design tools are also evolving, including, for example, increased emphasis on combination with data, digital twin concepts, or integration with virtual and augmented reality tools (Wu et al., 2022; Carberry et al., 2023).

Given this changing landscape in the field of process design, we present the outcomes of an extensive survey conducted on teachers/instructors of process design around the world to understand the state of the art in teaching process design in chemical and biochemical engineering. Similar surveys were conducted by Silverstein et al. (2013), and by Ford et al. (2023), with the second of these focussed only on university practice in the USA. Changes in subject matter, methodology and teaching strategies in the last decade apparent from the responses of our survey are highlighted to understand recent trends, as well as develop a vision on how process design could be taught in the future.

2. The 2023 Survey on Process Design Teaching Practice

2.1. About the survey

A survey to learn about the teaching practice of chemical process design was sent to more than 160 academic colleagues around the world, most of which are known to be associated with their institutions' efforts in teaching chemical process design. A particular effort was made to reach out to the leading schools teaching chemical engineering in the highest-ranked universities (e.g., the top 10 schools in the QS World University Rankings of 2021 and 2023). At the time of writing, we have received 40 responses to our survey; the final version of the paper will be updated to include any additional responses that will be received by January 2024.

The purpose of the survey was to learn how chemical process design is taught in universities around the world. The central question is to determine to what extent design activities are taught in one or two design-specific courses at the end of the degree in chemical engineering (i.e., capstone design), rather than exposing students to chemical engineering design during the entire degree. The survey consisted of three parts: I – general questions; II – questions on how process design is taught (specifically in capstone design); III – questions on how the process design project – if there is one – is administered and assessed.

We shall now provide a review of the results extracted from the 40 responses that we received, of which 58% were from European universities, 18% from North America, 13% from South America and the remaining 11% from Asia and Australasia. The responders are on the whole seasoned teachers of process design, with an average teaching experience of 13 years of teaching. The chemical engineering programs lead to either BSc or MSc, with an average degree length of 4.5 years. The average class size taught by the responders is 53, but with a large standard deviation (36).

2.2. What is taught in the capstone process design course

“No one thinks the courses are easy and most students are glad they took them after they have graduated but find them challenging when they are taking them.” *Marnie Jamieson, University of Alberta*

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As shown in Table 1, the technical skills taught in the capstone design course are those one would expect, with most institutions teaching the economic considerations associated with process design (e.g., plant cost estimation and profitability analysis), as well as technical design skills (e.g., heat integration, process synthesis, and design heuristics). Subjects more related to individual unit operations are somewhat less prevalent in the reported curricula, even when including systems of these units (e.g., separation sequencing and reactor selection and reactor network design). The less commonly included subjects are (surprisingly) safety, and to an even lesser extent, plantwide control and LCA. Not shown in the table are the soft skills that are taught in the course.

Table 1. Which technical skills are taught in the capstone design course.

Technical Skill	% Responders
Plant cost estimation	97
Heat integration	94
Process synthesis	91
Profitability analysis	88
Design heuristics	88
Equipment sizing	82
Techno-economic assessment methods	76
Separation sequence design	74
Reactor selection/reactor network design	65
Safety	62
Flowsheet optimization/superstructure optimization	56
Plantwide control	35
Life Cycle Analysis (LCA)	32

Table 2 lists the tasks expected to be addressed by students in the design project. These follow naturally from the skills taught in the capstone design course, with a strong emphasis on equipment sizing, plant cost estimation and profitability analysis.

Table 2. Which technical skills are addressed by students in the design project.

Technical Skill	% Responders
Comparing design alternatives	100
Equipment sizing	95
Plant cost estimation	95
Profitability analysis	95
Flowsheet synthesis	92
Flowsheet simulation	86
Pinch analysis	68
Environmental constraints	65
Heat exchanger network design	59
Safety analysis	51
Optimization	46
Comparing alternative raw materials	38
Uncertainty/sensitivity analysis	35
Carbon footprint analysis	35
Process control	32

The respondents were asked to list the textbooks that are used to teach the capstone chemical design course, and as seen in Table 3, many schools do not rely on a single book, which makes sense, given the nature of process design. The leading texts that are

used the most are Sinnott and Towler (2020), Seider et al (2017), and Turton et al (2020), in that order.

Table 3. Which textbooks are used in the capstone design course.

Textbook	% Responders
Sinnott and Towler (2020)	65
Seider et al. (2017)	63
Turton et al. (2020)	53
Peters et al. (2003)	48
Biegler et al. (1997)	33
Smith (2005)	33
Couper et al. (2012)	23
Kemp and Lim (2020)	18
Adams (2022)	13

“The origins of Chemical Engineering lie in Industrial Chemistry, however in the era of digitalization: as an educator, to establish a balance between process simulation and conventional hand or spreadsheet calculation is sometimes a challenge.” *Asad Sahir, IIT Ropar.*

Several questions were directed at elucidating which simulation software packages are used in the capstone design course, and how students are instructed in their usage. 78% of the responders indicated that simulation software is used extensively, with a further 15% stating that it is used to a small degree. Table 4 indicates that about half of the respondents are using ASPEN Plus, with the rest relying on other packages. With regards to training, 55% of the responders indicated that the use of simulation is taught either as part of the capstone course or in a separate course that is taught in parallel. 38% of the respondents indicate that the use of simulation is taught separately before the capstone design course. Only 3% of the respondents report that students are expected to acquire these skills on their own with no support.

Table 4. Which simulation software is used in the capstone design course.

Simulation software	% Responders
Aspen Plus	50
Aspen HYSYS	18
Honeywell UniSim	10
AVEVA PRO/II	8
gPROMS	5
CHEMCAD	3
GAMS	3

2.3. How is the capstone process design course taught.

“Although most of the students learn how to do the expected tasks/calculations mechanically using process simulation, often they do not achieve ‘junior competencies’ on process design as expected at the end of the course (e.g., why they should do the different tasks as they do them?). The previous background of the students (e.g., lack of emphasis on ‘decision making’ in previous courses), and the time/effort allocated to this topic are real constraints.” *Antonio Espuña, UPC - Technical University of Catalonia*

The core skills for process design are taught systematically year-by-year for the entire degree in 43% of the cases. A capstone design course is taught in the second to last year of the degree in 50% of the cases, and in the last year of the degree in 70% of the cases. The capstone design courses are taught by professors and lecturers, with the assistance of TAs in 43% of the cases, industrial adjuncts in 48% of the cases, and some assistance

from the simulator providers in 10% of the cases. In most cases, the capstone process design class is taught using a weekly combination of lectures (average length of 2 hours), recitations/exercises (average length of 1 hour), meetings with students (average length of 1 hour), and office hours (average length of 1.5 hours).

The design project is included as part of the capstone design course by 64% of the respondents, another 33% having the design project as a separate course, and 3% having no design project. The average project group size is five students (standard deviation, $STD=2$). The distribution of assessment of student mastery by categories is listed in Table 5, where the average weights and their standard deviations (STD) are presented. The large variance is due to 25% of the responders indicating that students are not examined in their courses, with the project grade being heavily dependent on the project and course performance of the students.

Table 5. How are the students of the capstone design course assessed?

Category	Average Weight (%)	STD (%)
Course progress	8	9
Project (group assessment)	32	20
Project (individual assessment)	17	22
Project presentation	12	10
Soft skills assessment	5	6
Midterm exam	8	12
Final Exam	18	20

Figure 1 shows the distribution of total meeting time used in the capstone design course by lecturers and TAs to present materials, with the rest used for Q&A, and other in-class activities (e.g., problem solving). The responses received indicate bimodal distributions in the time-utilization for active learning in both lectures, shown in Fig. 1(a), and recitations/exercises, shown in Fig. 1(b) – with a close to even split between those who utilize the time in favor of hands-on problem solving by students, and those who favor more traditional usage of the time to transmit information by lecturing. The positive impact of active learning on learning outcomes in process design education have been reported by Lewin and Barzilai (2021). These distributions are closely related to the even split between responders using recorded lectures and those who are not.

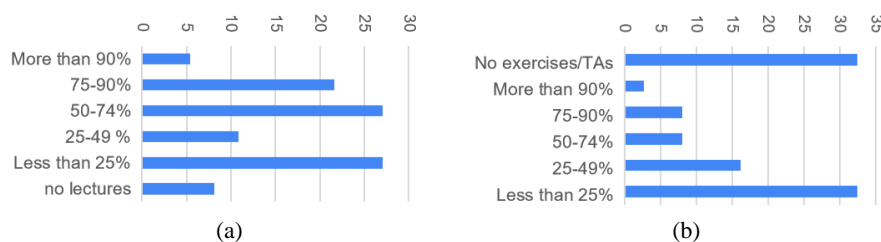


Figure 1. Percentage of time used to transmit information (AKA “lecturing”) by (a) teachers in lectures, and (b) TAs in recitations/exercises.

3. Conclusions

Given that the current version of the paper reflects the feedback from only 40 responders, it is a little premature to draw final conclusions from our study. We hope to be able to provide a clearer picture in the course of 2024, when we can rely on a larger sample among responders. However, even on the basis of the available information, it is clear that process design is perceived as a central activity in chemical engineering, with the

focus being on practical process synthesis and the associated techno-economic analysis as applied to industrial-scale problems. This skill set is unmatched by any other activity in the chemical engineering curriculum (Kiss and Webb, 2021). Results regarding soft skills were not reported due to space constraints but will be detailed in a later version as these skills can be ideally trained in the process design education. Finally, it appears that carbon footprint analysis, LCA and process control currently receive low priority in the process design and design project. To meet the UN SDG on sustainable production and consumption and to be in line with Industry 5.0, these areas should be taken more seriously in future teaching of process design and in the design project.

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