



Agile process systems engineering education: What to teach, and how to teach

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ABSTRACT

This paper investigates the current and future trends in the teaching of Process Systems Engineering (PSE) topics, addressing what should be taught and how these topics should be taught effectively in a classroom setting. It addresses which key PSE topics should constitute the core requirement of chemical engineering education and which application areas should be included. We surveyed existing courses on novel aspects of PSE applications, as well as polling PSE stakeholders to ascertain their opinion of what is taught and the degree to which graduates skills match their expectations. Existing gaps and interesting prospects have been revealed by the surveys leading to suggestions for the future. The second part of the contribution addresses how best the PSE content should be taught, so that our graduates are equipped to effectively apply their knowledge, given the availability of teaching technologies and the time available to effectively educate our students.

1. Rationale and background of the work

Process Systems Engineering (PSE) is the branch of the chemical engineering discipline that exploits computational methods and tools for the analysis, design, control, optimization, and effective operation of processing systems, and the design of products, across different scales and dimensions. In the context of Chemical Engineering, the field of PSE has been active for more than 50 years. Prof. Roger Sargent, founder, and pioneer of the PSE field defined it in the mid-60's as the development of systematic techniques for process modeling, design, and control (Sargent, 2004). Subsequently, a large number of academics and researchers have made significant developments and contributions to advance and expand PSE principles in many directions.

Several inspiring works have been recently published that highlight prospects and critical points that need attention for the future of PSE

education. (Gani et al., 2020; Grossmann and Harjunkoski, 2019) describe in detail the current status, discuss the future academic and industrial perspectives of PSE, and summarize the results of their survey on the standing of PSE in academia and industry. The authors also outlined critical issues such as the disconnect between academia and industry with regards to the appreciation of PSE and the role of stakeholders to disseminate the crucial role of PSE in the academic content and the profession of graduates. In a recent work, Pistikopoulos et al. (2021) analyzed the needs of PSE for the next generation in terms of basic principles, research, practical implementation as well as education. Their work adopts a hierarchical model representing the education needs, starting from the core, and proceeding to the outer layers (Gani et al., 2020). The authors consider the Circular Economy as the framework for future PSE expansion and developments. Cameron et al. (2019) have expressed - possibly for the first time so clearly - the relevance of

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PSE to the so-called Grand Challenges that require holistic approaches. Their work provides the insight of PSE as an integrative discipline in chemical and process engineering. The authors suggest an integrated framework for the design of PSE curriculum, mainly aiming at the development of technical knowledge as well as the mindset to approach problems in the PSE way.

This increased interest in educational needs for PSE highlights the need to match educational activities to a rapidly changing engineering world as well as the recognition of the impact PSE may have in all the great challenges in the years to come. In that respect, the present work should not be considered as just one additional contribution. It supports the ideas in play and takes the discussion one step further.

The methodology that has been followed in the present paper has a number of characteristics that result in a novel contribution in the field. More specifically:

- It is a team effort, in which many authors from different universities and countries have contributed by bringing their own experiences and knowledge.
- After a detailed state-of-the-art review, a comprehensive survey of the actual topics and application areas covered in the courses taught in academia, and two surveys that received responses from PSE stakeholders around the world (developers, researchers, and management) that map the education perceptions of PSE have been included. Therefore, real data have been collected, something that is not easy or common.
- Live, synchronous interviews with four pioneers in the field have taken place in an effort to extract their valuable experience in PSE education and research.
- An experimental workshop for novel PSE course development was run during the CAPE Forum 2022.

This paper is an extended and detailed version of two contributions in ESCAPE '32 (Kondili et al., 2022 and Lewin et al., 2022a). It proposes a “game plan” for effective teaching of PSE topics that addresses *what* should be taught and *how* these topics should be taught effectively. We base our recommendations on: (a) A survey of the teaching methods used by professors teaching PSE concepts and tools in universities around the World (the “How”), and (b) Surveys of the actual topics and application areas covered in the courses taught in academia (the “what”).

All topics taught under the PSE umbrella benefit from more time on task made available for students to learn by class discussion, experimentation, and cooperative solution of open-ended problems – basically by “getting their hands dirty” – as a key component of their own learning process. Courses taught using the conventional teacher-centered, lecture-based approach have less time available for these crucial activities, and thus may achieve lower levels of learning outcomes. In particular, the flipped format moves the lecture material online, to be completed by students as homework. Thus, the main justification to move to flipped format is the desire to increase the proportion of the student-staff contact time in which students are actively learning, rather than just listening to lectures (Crouch and Mazur, 2001; Felder and Brent, 2015). This makes better use of the shared time between teacher and students, which has a huge impact on students’ engagement, as does aiming to maximize the degree to which students are participating actively with the teacher and with each other, rather than passively listening to lectures. There are many existing studies that provide quantitative evidence that active learning improves course outcomes (e.g., Freeman et al., 2014, Velegol et al., 2015; Lewin and Barzilai, 2021). In an extended study involving secondary and post-secondary education, van Allen et al. (2019) found that the flipped classroom has a small positive effect on learning outcomes, but uncertain effect of student satisfaction, noting that the results depend strongly on how flipping is implemented.

There is an imperative to implement the most effective methods to achieve learning objectives that enable graduates of the first degree in

chemical engineering. In particular:

- Students should be taught fundamental concepts in detail, ideally self-paced. This is achieved more efficiently using prerecorded materials.
- Students need to be exposed to computer programming packages ranging from those solving chemical process flowsheets to those specialized in data analysis, optimization, and spreadsheets.
- Students need to understand why some software or computer packages may not provide accurate answers in some instances. The fact that they run and converge to a solution does not necessarily mean that the solution is correct.
- Students should become familiar with optimization tools earlier in their academic career, so that they can use them to solve practical problems in their senior years. Students should apply multivariate statistical and artificial intelligence tools for solving real problems.
- Students should be required to develop critical thinking skills, i.e., to question their solutions/methods and ask themselves if other (attractive) approaches could be used to tackle a particular problem.
- Students should develop professional and personal skills such as teamwork, communication, and project management.

This study consists of a survey of teaching practices aimed to assess the degree to which active methods are used in practice, to understand their benefits, limitations, and potential reasons as to why they are not implemented, and to identify circumstances or the conditions under which these methods may be more effective. This paper therefore provides a working plan for academic activity in preparing the next generation of engineers and researchers to be better aligned with the needs of both academic research, industry, and society, without requiring additional time on task beyond that allocated currently for the coverage of PSE topics.

The paper is structured as follows. In Section 2, we review the current status of PSE education, and in particular provide a status of the current scope of courses taught under the PSE umbrella. From the introduction above, we have indicated the need to move to active learning methods in PSE education. Accordingly in Sections 3 and 4, we discuss the link between active learning and learning outcomes and provide an overview of the components of the proposed flipped class approach, as well as details of what is required from the point of view of the lecturers and the benefits for students, with a focus on guidelines for practice that works, as well as evidence for the contribution of the proposed teaching methodology to learning outcomes. In Sections 5 and 6, we present the results of the two surveys conducted to gauge the positions of academics and industrial practitioners with regard to the PSE curriculum and PSE teaching practice. The paper ends with our conclusions.

2. Current status, contents, and prospects in PSE education

This section surveys the PSE related modules being taught in some selected undergraduate and postgraduate courses in Europe, Asia, USA, and Canada. Clearly, there are Chemical and Biochemical Engineering courses with a strong presence of PSE related content without the presence of PSE modules as such. As pointed out by Cameron et al. (2019), the presence, breadth and depth to which PSE is included in the curriculum of a Chemical and Biochemical Engineering program depends strongly on the number of faculty members with a background or research focus on PSE. Other relevant parameters may be the presence of a strong process industry, the attitude and focus of academics and industrialists to cooperate (e.g., forms of industry – academia cooperation, such as in Imperial College London), the recognition of PSE expansion in other strong areas such as the energy field (e.g., Texas A&M, USA), and the creation of, and local activity in, computer science and technology capacity. The modules present in almost all undergraduate Chemical and Biochemical Engineering undergraduate curricula that have PSE

content are the ubiquitous courses covering integrated process design, process dynamics and control, and often courses in process modeling, simulation, and process optimization. In some universities where the undergraduate program is not specifically focusing on Chemical Engineering (CE) but more generally on engineering, PSE courses may be only briefly introduced at undergraduate level, while most PSE modules are taught at postgraduate level (e.g., Léonard et al., 2017).

In a few universities, PSE-focused postgraduate studies are also carried out in dedicated MSc courses, also including research dissertations in the PSE field. However, it should be emphasized that the relevant PSE education content in the key societal issues such as energy, environment, water, pharmaceuticals, water-energy-food-environment nexus is often lagging behind the relevant focus of PSE research in these fields. A number of courses have also been found, mainly in MSc programs, such as big data methods and modeling in chemical engineering (CE), supply chain planning and scheduling, process and energy integration, energy systems optimization and process intensification, knowledge-based systems and AI, process safety and operations integrity, advanced environmental engineering; transition to a low carbon economy, modeling of biological systems, advanced bioprocess engineering, multivariate statistics in CE. These courses are found mainly in postgraduate programs since the capacity of undergraduate courses is usually limited to more basic subjects.

In the context of the state-of-the-art review, in addition to the detailed survey of existing courses in various universities worldwide, we also carried out personal interviews with four world class pioneers in the PSE field, namely (in alphabetical order)

- Prof R. Gani
- Prof I. E. Grossmann
- Prof C. C. Pantelides
- Prof S. Pistikopoulos.

The issues that have been discussed include:

- What in their opinion is the current status of PSE education and the profession
- What are the perspectives of PSE as a distinct field within the CE curriculum
- What should be the knowledge and competencies of PSE graduates in order to be able to respond to industrial and professional needs in the field
- How should PSE education change and ultimately whether they believe that PSE will continue in future years to exist as a distinct field within CE addressing real needs.

The discussions – carried out during February and March 2022 – have really been very valuable and enlightening in our thoughts for the *what* and *how* in PSE education. Below are some of the points of these discussions with their opinions and thoughts being highlighted.

- It is not an issue whether or not PSE “standalone” content belongs in CE studies. The important issue is that students understand the fundamentals of process engineering. Therefore, PSE should be embedded within the basic and fundamental CE modules.
- Modeling should be embedded in all CE courses and this approach should be transferred to students straight from the beginning of their studies.
- The Chemical Industry’s future is obscure, and it definitely needs to change. Therefore, not only PSE but the whole of the Chemical Engineering discipline will need to change to adjust to future needs.
- In the USA, PSE graduates get multiple offers, and they get good jobs. This is not the situation for the other CE specialisations. The reason is, and should continue to be, the strong links of PSE with industry.

- Life Cycle Assessment (LCA) and Supply Chain Engineering and Management are very promising fields within PSE, as well as Operations Research.
- Problems like waste valorization, refineries decarbonization are of very big interest.
- In terms of the content of PSE modules, the basic courses of process modeling, process control, simulation, and optimization should remain in undergraduate studies (when applicable), whereas more advanced courses like AI, data mining, as well as all the courses related to circular economy, energy and global challenges in general should be included in postgraduate studies.

3. Teaching PSE using active learning

PSE topics are challenging to teach and to master since they all address the three top tiers in Bloom’s Taxonomy (Bloom et al., 1956): analysis, synthesis, and evaluation. Ideally, a combination of examinations and group project assignments are the vehicles for assessing students’ knowledge and competencies in all PSE topics. These are the ‘common’ assessment types. Introducing such assessment as oral defenses gives much better insight in to mastery. However, such alternative assessments are limited to relatively smaller classes. The utilization of project outcomes for assessing individual competency requires careful checking to ensure all team members are truly contributing. For example, most process design courses also include a competitive design project component, calling for a demonstration of team-effort in addition to individual mastery. While both team and individual capabilities are important, examinations provide a more reliable measure of the crucial mastery of individual students (Turton et al., 2013). Evidently, assessment is the most difficult and least mastered part of an academic’s responsibilities. Bloom (1968) postulated that the degree to which students achieve mastery depends on four conditions:

- 1 *Clear definition of what constitutes mastery.* It is the responsibility of the course instructor to clearly state the learning objectives in a manner that defines precisely what students need to achieve to demonstrate mastery. Rather than knowledge, this definition may also cover complex competencies such as the ability to critically identify and use information sources, or the ability to deal with discrepancies and/or incomplete information (EFCE, 2010). In this case, such competencies need to be illustrated with examples beforehand for the students to understand what they are expected to achieve.
- 2 *Systematic, well-organized instruction focused on student needs.* We suggest an approach based on pre-prepared, clear presentations of the course materials in which online lectures are composed of short video segments interspersed with practice activities, to enable students to actively control their initial acquisition of the basic materials. Then in the class meetings and active tutorials, students practice on more complex and advanced example exercises, first in cooperation with the course staff, and then on their own and with their peers. This sequence of actions leads to weekly cycles of systematic learning.
- 3 *Assistance for students when and where they experience difficulties.* The active tutorials, where students are expected to come to grips with problem-solving by themselves or working in small groups, are the ideal vehicle to aid students when they need it most: the first time when they attempt to solve example problems for themselves. This increases the likelihood that mastery will be achieved in less time.
- 4 *Provision of sufficient time for students to achieve mastery.* This implies the need to increase the time allotted to active tutorials at the expense of time expended in teacher-centered lectures and demonstrations. This is the reason for the shift to switch lectures to online homework activities, which is the basis of the flipped classroom.

Bloom (1968) reports the modes of learning that improve outcomes,

with the most significant obtained by personal tutoring, which increases the degree of mastery as exhibited by exam grades up to two standard deviations higher than for students taught by a conventional lecture-based approach. Amongst other factors indicated by Bloom (1984) as having significant positive effects on achieving learning mastery, are positive reinforcement and praise from the instructors, student classroom participation and time on task. Bloom reports that all these factors improve results by approximately one standard deviation higher than achieved by conventional lecture-based instruction. In a more recent supporting contribution, Felder et al. (2000) opined that effective teaching combines the formulation of instructional objectives with the use of active and cooperative instructional methods.

The main justification to move from traditional lecture-based teaching is the desire to increase the proportion of the student-staff contact time in which students are actively learning rather than just listening to lectures. This format makes better use of shared time between teacher and students to significantly impact students' engagement, as does aiming to maximize the degree to which students are participating actively with the teacher and with each other, rather than passively listening to lectures.

For students to attain mastery in the critical understanding and application of the PSE core materials, time needs to be allocated for them to experiment, get things wrong and understand why – repeating this process as many times as needed (Kapur, 2015). Such student-centered, active approaches to learning require time, which in a conventional teacher-centered approach is often allocated to lecturing. Several methods have been advocated that free class time for students to engage in active learning such as project-based learning (PjBL), blended teaching, and flipped class approaches. Moreover, recently the use of virtual laboratories in chemical and biochemical engineering has been explored (Caño de las Heras et al., 2021). Such tools can complement active learning strategies but will not, on a stand-alone basis, provide as much value as they are intended for. The flipped class paradigm, detailed by Lewin and Barzilai (2021 and 2022), moves the transmission of basic information to online preparatory tasks, which students complete in advance of class activities. This freed class time enables the four key agile values to be incorporated into the class environment, i.e.,

- 1 Student-centered flipping inherently focuses on the learner rather than following traditional teaching processes, which are teacher centered.
- 2 Student-staff contact time is mostly used to work problems cooperatively and for project work, rather than for the transmission of information.
- 3 The contact time is largely reserved for collaborative work between staff and students and transforms the staff member to take on the role of mentor and motivator, who encourages the learning of students rather than delivering them knowledge in one-way communication.
- 4 Staff can respond to the feedback and needs of students.

4. Learning enabled by the flipped class

This section begins by a summary of the three phases of the flipped approach as implemented at Technion (Israel). It then details the demands on teachers who choose to adopt it in their courses, the benefits to their students, and presents evidence of the benefits that can be expected from the application of active methods.

4.1. The recommended flipped approach

Three PSE topics, process design, process control and plant design, have been taught annually at Technion using a three-phase flipped approach, the first of which since 2015, and all three online since the COVID-19 pandemic struck. In this approach a weekly cycle consists of three steps:

- (a) Asynchronous assignments in which pre-recorded video lessons are completed in advance of the week's activity by students as homework. Moodle lessons (<https://moodle.org>) are used as a framework for these, with each lesson being composed of a series of questions in which short video segments of lecture material are embedded.
- (b) Synchronous class meetings, using Zoom or in face-to-face/hybrid sessions, in which students interact with the lecturer and with each other. Typically, these involve review of concepts from the online lesson, discussions generated by quiz questions, and open-ended problem solving.
- (c) Synchronous active tutorials, using Zoom, in which students solve example problems for themselves. These usually begin with a brief review by the teaching assistant followed by problem solving by students working separately or in groups, utilizing breakout rooms. Our Technion experience is that active tutorials run in Zoom breakout rooms are more effective than tutorials in regular face-to-face settings.

4.2. Requirements from the lecturer

The flipped format implemented imposes significant effort on the part of the lecturer:

- (a) Online materials, namely, the prerecorded lectures involving 5–15 min video segments and associated quiz questions need to be prepared, most effectively using a video editor such as Camtasia® (<https://www.techsmith.com>). Each course typically requires of the order of 100 each of video segments and quiz questions, which constitutes a huge investment. However, this effort is only invested once: the author prepared the materials for the process design course in 2015, for the process control course in 2017, and for the plant design course in 2020 (Lewin, 2022). No additional preparatory materials have been required for either course since the initial resource development.
- (b) The lecture time freed by moving lectures to online homework tasks for students to do on their own needs to be occupied by suitable activities. The main difficulty for many teachers, especially those who are used to just lecturing, is the required change in their mind-set, which shifts the contact time between lecturer and student from being teacher-centered to being student-centered. This means that class materials should be designed to support open-ended problem solving performed by the lecturer but stressing class participation, the use of pop-quizzes to generate class discussion on their solutions, and any other activity that will enhance students' understanding. The development of these activities will take time to get right, and will likely evolve over time, as teachers become more accustomed to this mode of instruction.
- (c) The active tutorials could be as simple as just having students solve what used to be homework exercises working in teams in recitation time, or more involved and specially designed exercises. The main objective is to ensure that the students are doing most of the work for themselves.
- (d) Flipping may be new to some students. It is important to define parameters in the first class meeting by explaining to students how the system works, what are the benefits, and what is required from them.
- (e) It is important to continuously monitor the activity of each student, and follow-up on those students who are less active or

struggle with the course. This task is facilitated by a myriad of tools that are available in learning support systems.¹ By harnessing these tools, the instructor can reach out to the less-engaged students in a timely manner, by dedicated in-person mentoring.

4.3. Benefits to the students

Low-performing students typically do not significantly engage during the semester, leaving most of their effort for cramming just before final exams. This behavior is unlikely to achieve mastery of the taught materials. In each week of a course taught in flipped format, students need to prepare for the class meeting and active tutorial by covering the pre-prepared materials ahead of time. They then benefit from participating effectively in the class meetings, by responding to the pop-quizzes, contributing to class discussion and brainstorming during the open-ended problem solving. Finally, they participate in active tutorials where they solve exercises for themselves, mentored by the course staff. This combination of activities increases the performance of the entire class, as will be described next. Flipped-class learning is often criticized as leading to larger workloads for students. This is not necessarily the case, as the total weekly load expected from online learning, and attending class meetings and active tutorials is the same as the load resulting from attending regular lectures and tutorials, and then doing homework at home. Indeed, provided that students do engage in the flipped-class approach, their total time invested to achieve mastery is more efficiently used, as they are actively engaged throughout. Time invested may in fact decrease.

4.4. Class experience with the flipped teaching method

As reported in Lewin and Barzilai (2021), process design has been taught at Technion for the last twenty years using the full spectrum of possible approaches. This began with traditional teacher-centered instruction, in which the course materials were transmitted via lectures and demonstration-recitations to the students, termed Phase I. The first transition was to active tutorials, where at least students were actively engaged in problem-solving for themselves, termed Phase II. The last major change, Phase III, was the move to the flipped classroom paradigm in 2015, which freed even more time for students to get to grips with the course material for themselves. Process control and plant design are both now also taught at Technion in flipped format as previously described.

As described in Lewin and Barzilai (2021), the outcomes achieved by the students of the process design course have incrementally improved over the last 15 years, as illustrated in Fig. 1, which shows a bubble plot showing disks whose relative diameters are in proportion to the fraction of the high-performing students in each year's class, centered on coordinates, whose ordinate and abscissa are the average grades of the high- and low-performing subsets of the class in each year, μ_1 and μ_2 respectively. These parameters are determined by fitting a bimodal distribution to actual exam grade distributions using the approach of Lewin (2021). Note that as $\mu_1 \geq \mu_2$ by definition, all disks have to be centered under the dashed line $\mu_1 = \mu_2$ indicated in Fig. 1. The best performing classes would be those represented either by disks of any diameter in the top right of the plot (high average exam grades of both high- and low-performers, irrespective of their proportions), or lower on the right with large diameters (high average exam grade of high-performers, whose proportion dominates the population). Conversely, classes represented by disks on the left would be characterized by low average exam grades of the high-performers, and even

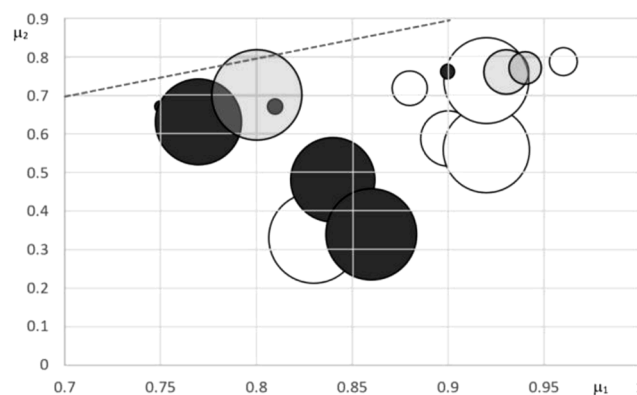


Fig. 1. Bubble chart summarizing binomial distribution diagnosis (adapted from Lewin and Barzilai, 2021). The statistics for each year are centered on the $\mu_1 - \mu_2$ plane, with the disk diameter proportional to p . The disks are color-coded according to period: black – Phase I: 2005–2010 (before active tutorials), gray – Phase II: 2011–2013 (before flipping), white – Phase III: 2015–2020 (after flipping). The dashed line indicates $\mu_1 = \mu_2$.

lower average grades of the low-performers. As can be seen in Fig. 1, the class disks for Phase I, shown in black, are on the left. The transition to Phase II indicates a shift to the right, maintained after the transition to the flipped class in Phase III.

As discussed in Lewin (2021), most exam distributions are to some extent bimodal. These could be due to inherent heterogeneous capabilities of the students in the class, or the consequence of the degree of engagement in the course materials. Certainly, there is evidence for the link between engagement and final exam grades, as shown in the example data in Fig. 2 in which the exam grade distribution in the final exam of the process control course in 2021 is shown in comparison with separate distributions – one for the 20 students that attended active tutorials the least, and other distribution for the 20 that attended the most. Note that whereas the average exam grade for the entire course was about 70.1%, the average grade of the 20 students that attended the most tutorials was 78.7%, while that for the 20 least-attending students was 60.5% – more than one standard deviation lower than that achieved by the most-attending students.

5. Survey 1 – “What should be taught in PSE?”

5.1. Objectives of the survey

As a complement to the review of actual teaching practice, we carried out an online survey to obtain the opinions from PSE stakeholders (developers, researchers, users) to map the education perceptions of PSE around the world. The survey asked the responders to establish their position regarding the content of PSE education and its response to current and future needs. This questionnaire was termed the “What” survey, delivered using Google Forms, and distributed via email links to the global PSE community. The “What” survey consisted of 16 questions and was organized into three main categories:

- Information about the responder (Q1-Q3 on the nature and size of business, geographic location, Q4 on how responder views PSE skills as critical)
- Questions relating to the responder's position on aspects of the PSE and CE in general curriculum outcomes.
- Questions relating to how the responders' organizations use PSE methodology.

To collect as many responses as possible, we reached out to the following communities: the EFCE CAPE Working Party members, EUR-ECHA members, the Energy Section of the EFCE, the AIChE CAST

¹ For more implementation details about the flipped classroom as implemented at Technion, see the YouTube video: https://www.youtube.com/watch?v=O3hoSIYaGo4&list=PLW3u28VuDAHIQHCEm8Vq30_Et_2chWFyO

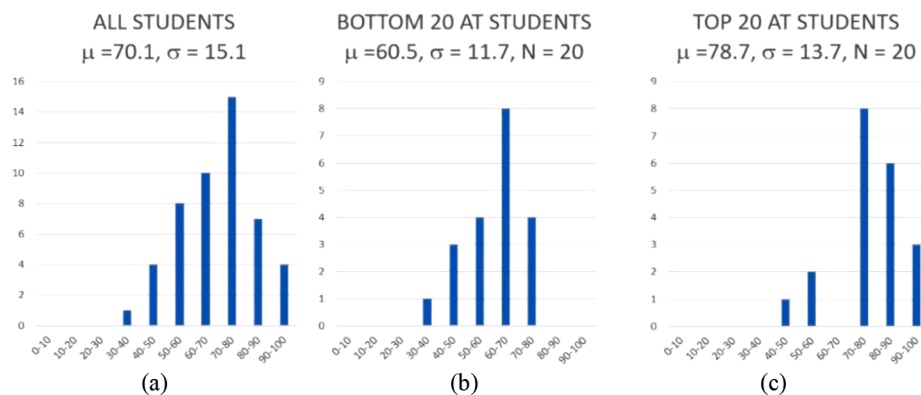


Fig. 2. (a) 2021 Process control course outcome distribution for the entire class and separate distributions for (b) the 20 students that attended active tutorials the least and (c) the 20 that attended the most, out of a total of 50 students examined. In the histograms, abscissae indicate numbers of students, plotted against exam grade bins.

Division, the CACHE Corporation, the master list used to promote PSE 2018, the Systems and Control Division from Canada and the Japanese PSE community. The total number of responders was 142: 92 from academia and research and 50 from a wide range of industries (i.e., process industry, software development, and consulting companies). The respondent's geographical distribution is: 40% Europe, 21% USA, 27% Asia, 10% Central and South America, 2% Australia/New Zealand. About 50% of the responses were from very large organizations (more than 5000 employees, with a further 25% from large organizations (500–5000).

5.2. Survey results

The responses to the 16 questions establishing the positions of responders in Parts A, B and C of the survey were distributed on a 5-point Likert scale, where 1 indicated strong disagreement, 3 indicated a neutral position and 5 indicates a strong agreement. Tables 1–3 summarize the average and standard deviation of the received responses to the 16 position questions.

5.3. Discussion of results

The responses to the specific questions are presented in Tables 1–3. One of the interesting issues of this part of the survey is that it has been answered by responders from both academia and industry, and thus, are weighted averages from both communities. However, separate analysis for the two groups indicates that there is no significant difference between them. The responses from industry in general avoid extreme opinions (i.e., “not at all” and “very much”). Almost all the responders (94%) believe that PSE is a key factor that contributes to the knowledge and capabilities of freshly graduated chemical engineers. The responders certainly are PSE experts or with PSE knowledge and this affects the survey's outcome. But the general opinion is that young

Table 1

Statistics and response distributions of the received responses to the position questions of the “What” survey, Part A: Your position on the importance of PSE.

Question	Question statement	Ave	STD	Histogram
WQ4	To what extent do you consider PSE skills as useful in developing a career as a chemical engineer?	4.42	0.62	

Not surprisingly, given the PSE-related organizations who were polled, 94% of the responders considered PSE skills as either important or vitally important to developing a career in chemical engineering.

Table 2

Statistics and response distributions of the received responses to the position questions of the “What” survey, Part B: Your position on aspects of PSE curriculum outcomes.

Question	Question statement	Ave	STD	Histogram
How close to your expectations are the skills of freshly-graduated chemical engineers in the following areas:				
WQ5	Fundamentals of chemical engineering	3.27	0.76	
WQ6	Practical engineering design capabilities	2.79	0.78	
WQ7	Critical thinking	2.95	0.87	
WQ8	Mastery of process analysis and synthesis software packages	3.18	0.86	
WQ9	Computer programming skills	2.77	0.90	
WQ10	Professional and personal skills (group work, presentation, writing)	3.13	0.84	
Some responders made comments related to the reliability of the results due to the very wide nature of questions. One comment is quoted due to its significance: “The students have high critical thinking, but it is not only due to PSE... We are very familiar here with ‘advanced’ tools and methods from PSE, but this area lost some way in some sense. Even with Optimization, Design and Cyber Physical Fusion, the real sense is very important. All computer aided design tools must be used with some discretion and engineering judgment on the part of the designer. This judgment mainly comes with experience. The art and practice of design cannot be learned from books. The intuition and judgment necessary to apply theory to practice will come only from practical experience.” (G. Towler)				
The last question in this part of the survey refers to the impact of teaching innovations on skills				
WQ11	Do you see a positive effect of innovative teaching methods on the capabilities of freshly-graduated chemical engineers?	3.23	0.97	

graduates appear to be rather mediocre in chemical engineering fundamentals, practical engineering knowledge, personal and professional skills, and particularly low in design, critical thinking, and programming skills.

On the other hand, it is very clear from the responders that they have been using PSE methods and tools to address climate change and sustainability issues but to a lesser extent, supply chain management and

Table 3

Statistics and response distributions of the received responses to the position questions of the “What” survey, Part C: How your organization uses PSE methodology.

Question	Question statement	Ave	STD	Histogram
To what extent is your industry/research involved in/using computation tools in:				
WQ12	Enhancing sustainability or addressing climate change	3.39	1.25	
WQ13	Production planning, schedule-ing or supply chain management	3.20	1.22	
WQ14	Safety and risk management	2.87	1.17	
Perceived value of PSE				
WQ15	How do you value of PSE in driving business?	3.52	1.03	
WQ16	Extent of in-house capability to conduct PSE projects	3.72	1.09	
WQ17	Degree of in-house develop-ment or implementation of Industry 4.0 projects	3.19	1.20	
WQ18	Would you consider bringing in experts from outside to address PSE-related questions?	2.96	1.07	

planning/scheduling problems. In general, PSE is considered very important for their activities, and they are much interested in hiring specialised graduates to address PSE related projects.

The above results indicate serious issues not only for PSE related education but more generally for the ability and knowledge of graduates to understand the complexity of today’s industry and professional environment. Indeed, paraphrasing Pistikopoulos et al. (2021), there is no such thing as a chemical engineer that does not utilize PSE every day, everywhere. Therefore, PSE education needs to be totally integrated into the entire CE undergraduate curriculum to gain depth in different areas of application of chemical engineering and provide cases and expansion to all the relevant fields at a later stage. Courses in engineering computational tools, numerical methods, statistics, and engineering economics, essential in the PSE field, should be integrated into the engineering core of each curriculum.

To perform successfully, the chemical engineer must be able to design, analyze and control processes to produce useful and desirable products from less valuable raw materials in an efficient, economic, and socially responsible way. The integrated approach of PSE and its focus on modeling and systems thinking make a very important framework and it is not only a matter of separate modules but a way of thinking and a mindset that should be introduced from the beginning in the Chemical Engineering curriculum (Cameron et al., 2019).

5.4. Proposal for new PSE courses development methodology

From the previous sections, the lack of novel PSE courses in the undergraduate and postgraduate Chemical and Biochemical Engineering education has been identified. Therefore, it is clear that new PSE courses will need to be developed in the near future, in order to respond to real world needs and of course to strengthen PSE relevance and response to global challenges.

The development of a new course is a difficult task that undergoes a number of steps, with the course improving over time using experience from its implementation. In that respect an experiment has taken place in the recent CAPE forum in the form of a workshop (Lewin et al., 2022b), where the participants worked as teams on a master plan for four distinct selected subjects, namely:

Topic 1: Carbon-neutral PSE

Topic 2: Sustainable biobased PSE

Topic 3: Energy efficient PSE

Topic 4: Artificial Intelligence for PSE

The workshop was organized and managed by the leading author of this paper and the steps that have been followed include:

- The clear definition, the learning objectives and syllabus for the entire course.
- Learning objectives and syllabus for at least one week of activity in the course.
- Generation of suitable activities for students for each of the weeks of activity outlined above.

The global challenges to be addressed are novel and very rapidly changing. The relevant courses will include a part that introduces to the students the basic principles and the characteristics of the subjects under consideration, their relevance and potential PSE methods and tools for their solution. However, these global problems, such as energy efficiency, supply chain management, circular economy and sustainability, undergo rapid changes. The suggested courses will need to follow these changes and, therefore, should also include steps and procedures for their frequent updates.

It is a challenge for future work to make more concise suggestions for the above issues.

6. Survey 2 – “How should PSE be taught?”

6.1. Objectives of the survey

We used a survey to map the teaching perceptions of PSE academic teachers around the world. The survey asked the responders to establish their position regarding the application of active teaching methods, and then describe the extent to which active methods are used in one of the courses taught by the responder. Moreover, the responders were asked to discuss how they see their teaching will evolve, and to define barriers to future evolution of their teaching approaches. This questionnaire was termed the “How” survey, delivered using Google Forms, and distributed to the global PSE community.

6.2. Material

The survey consisted of 26 questions organized into five main categories:

- A Information about the responder (i.e., geographical location, teaching experience)
- B Questions regarding the responder's position on aspects of the PSE curriculum
- C Questions regarding the responder's position on how teaching should be carried out and, to the degree to which active learning should be applied.
- D Questions regarding the responder's teaching practice, and to what extent active learning is employed.
- E Questions regarding the responder's future adaptation of teaching methods.

6.3. Participants

To cover as many individuals as possible, we reached out to the following communities: the EURECHA members, the Energy Section of the EFCE, the AIChE CAST mailing list, the CACHE mailing list, the master list used to promote PSE 2018, the Canadian Systems and Control Division mailing list, and the Japanese PSE community.

6.4. Procedure

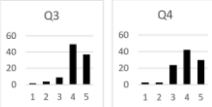
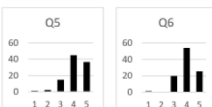
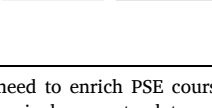
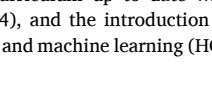
On 15th October 2021, a request for feedback with a link to the survey was emailed to all potential responders on the mailing lists described above, with a reminder sent on 22nd October. We received 82 responses from academic lecturers from all over the world, with the following geographical distribution: 47.6% Europe, 20.7% North America, 15.9% Asia and 13.4% Central/South America. Most of the responders (83%) had more than 10 years of experience teaching PSE courses, with an additional 10% having between 6 and 10 years of experience.

6.5. Analysis

The first two questions (HQ1 and HQ2) establish the geographical distribution and teaching experience of the responders. The responses to the remaining 22 questions establishing the positions of responders in categories B-E described above were distributed on a 5-point Likert scale (1 indicates strong disagreement, 3 indicates a neutral position and 5 indicates strong agreement). Tables 4–7 summarize the averages and standard deviations and presents histograms of the received responses to the position questions.

Table 4

Statistics and response distributions of the received responses to the position questions of the “How” survey, Part B: Your position on aspects of the PSE curriculum.

Question	Question statement	Ave	STD	Histograms
HQ3	Courses should be enriched with external sources or guest lecturers	4.17	0.83	
HQ4	Should offer courses using open access software	3.94	0.93	
HQ5	Should offer courses on advanced statistics	4.13	0.84	
HQ6	Should offer courses on artificial intelligence and machine learning	4.02	0.75	

Summary: There is general agreement about the need to enrich PSE courses using external sources (HQ3), and to maintain curriculum up to date with regards to the usage of open-access software (HQ4), and the introduction of courses in advanced statistics, artificial intelligence, and machine learning (HQ5 and HQ6).

6.6. Discussion

As seen in Table 5, lecturers are ambivalent concerning whether teacher-centered instruction is appropriate (HQ7) but tend to support the idea of students reviewing materials to prepare for class (HQ8) as well as the use of contact time to enable student activity (HQ9). Regarding recitations, the responders largely disagreed that staff should run them in demonstration mode (HQ10), and strongly supported the idea of active tutorials, where students do the problem-solving themselves (HQ11). Regarding outcomes assessment, there was high agreement that project-based learning should be employed (HQ12), agreement that individually graded homework should be assigned (HQ13), and that open-ended exams should be used for formative assessment (HQ14). Note that one should avoid requiring students to undertake both individual homework as well as preparation before classes, which may overload students. When it comes to their own teaching practice in lectures, Table 6 indicates that the responders were more ambivalent, with responses almost evenly split between those taking teacher- and student-centered approaches (HQ19 and HQ20). Regarding student activities, there are more instances of group work than individual work (HQ21), and a majority of the respondents include student activities in lectures and recitations (HQ22). Furthermore, the responders indicated that a majority regularly update their teaching materials (HQ23), and a large majority indicated the importance of using real-world situations in their teaching, which links to the importance of PjBL indicated by HQ12. Finally in addition, the main obstacles to teaching innovation (HQ25) are identified as the lack of time (65%), followed by the lack of institutional support (46%), but it also appears that not all students are welcoming innovative teaching methods (32%). In addition to the above, the survey also included two questions (HQ15 and HQ26) giving responders the opportunity to make general remarks.

7. Conclusions

Our findings propose a framework for academic activity in preparing the next generation of engineers and researchers to be better aligned with the needs of academic research, industry, and society. The first survey, the “What,” addresses the current practice and the perceptions of practitioners in both academia and industry about the appropriate content of PSE education. The aim, of course, should be to provide prospects and professional advancement to graduates as well as significant added value to industry for the most sustainable solutions to their crucial problems. Outcomes of the research and suggestions for the future include the encouragement of the PSE community to expand to fields related to novel challenges in classical problems such as sustainable supply chains or the societal issues of circular economy, water, food, energy engineering, where the PSE approach has a lot to offer, and PSE-specialised engineers will find new professional prospects.

Perhaps the time has come for educational modules to be developed to facilitate the introduction of these new areas into the PSE curriculum worldwide, for the benefit of both students and the PSE community. Since the COVID-19 pandemic forced all teaching to move completely online, one would have thought that this would have motivated the transition to active methods in teaching. In fact, teaching pedagogy has largely not been affected by the potential of technology, with much online teaching still teacher-centered, relying on synchronous lectures delivered over Zoom. The second “How” survey has indicated that the main obstacles to change are the following: time taken away from research activities (65%), lack of available institutional funding (46%), and student dissatisfaction with new forms of teaching (32%). Teachers are clearly discouraged both by the significant investment of time and effort required to prepare quality online materials (e.g. prerecorded lectures and online exercises), and by the initial resistance of some students to active learning. Not surprisingly, there is reduced outcome performance from the non-participants/non-engagers; Quantifiable lower outcomes are attained by students who engage less with the online

Table 5

Statistics and response distributions of the received responses to the position questions of the “How” survey, Part C: Your position on how should teaching be carried out in practice.

Question	Question statement	Ave	STD	Histograms
How course materials should be transmitted to students, and how best to utilize contact time				
HQ7	Classes should be organized so teachers mostly lecture, and students listen	3.16	1.18	
HQ8	Lecture materials should be reviewed by students on their own as homework in preparation for class activity	3.52	1.00	
HQ9	Most of the contact time between teachers and students should be used for student activity	3.56	1.03	
The responses indicate ambivalence regarding face-to-face lecturing as the main transmission vehicle (HQ7). There is slightly more support for moving materials online for students to cover on their own (HQ8) and for class time to be used more for student activity (HQ9). However, it is fair to indicate that this support was not overwhelming.				
How should most of recitation time be best utilized?				
HQ10	Instructors demonstrating solutions and students listening	2.68	1.01	
HQ11	Students solving problem sets with staff providing hints/motivating	4.04	0.80	
If responses are consistent, the two questions should have response distributions that are mirror images. The responses to HQ10 are bimodally distributed, with more disagreement than agreement – more responders do not approve of student passivity, but clearly many are comfortable with it. Moreover, HQ11 indicates that there is strong support of student activity in recitations. However, the distributions are clearly not inverted, as they should be for consistency.				
How should PSE course outcomes be assessed?				
HQ12	Include a significant portion of project-based learning (teamwork)	4.35	0.62	
HQ13	Students should do individually graded homework exercises	3.79	0.96	
HQ14	Using one or more exams involving open-ended problem solving	3.51	0.89	

The need for project-based assessment (HQ12) received strongly positive response. There were mixed feelings about the other two issues – while there is a slightly positive position regarding the need to check individual students’ formative abilities by grading homework (HQ13), the position does not have overwhelming support. The support for summative assessment (exams, HQ14) is moderate. The main issue is which kind of formative/summative assessment methods are the most appropriate given students’ time limitations. What proportion of assessment should be team or individual is crucial. That is likely to be more significant than the methods.

Table 6



Statistics and response distributions of the received responses to the position questions of the “How” survey, Part D: How do you teach?.

Question	Question statement	Ave	STD	Histograms
HQ16	Graduate (G) or undergraduate (UG) course: 28% UG, 53% Combined, 19% G			
HQ17	Subject taught: 48.5% Process design, 33.3% Process control, 15.2% Optimization, 3% Numerical methods			
HQ18	Class size:: 8.6% <10, 58% 10–50, 25.9% 51–100, 7.4% >100			
Slightly more than half of the responders teach mixed classes of graduate and undergraduate students, with 28% teaching only undergraduates and 19% teaching only graduates. Most responders are teaching either process design (49%) or process control (33%). Most class sizes are either medium-sized with 10–50 students (58%) or large with 51–100 students (26%).				
The following questions were directed at the type and mode of learning environment that exists in the responders’ institution.				
HQ19	Student-centered (>50% of contact time is student activity).	3.16	1.10	
HQ20	Teacher-centered (>50% of contact time, students are listening to me).	3.02	1.06	
HQ21	Students are required to work independently and not in groups.	2.74	1.07	
HQ22	Student activities are included into the lectures and recitations.	3.70	1.02	

The responses to HQ19 and HQ20 regarding how responders run their lectures are very similar and are both bimodally distributed. The responses are almost split 50/50 between those who teach in the traditional teacher-centered method (teacher talks – students listen) and those who apply student-centered, active learning in their classes. More detailed analysis indicates that much of the support for student-centered activity was by teachers of process design, and independent of the class size. HQ21 discloses the responders’ views on the need for students to work independently rather than in groups. The majority of the responders disagree with this statement, indicating there is some application of group effort in many of the responders’ courses. However, many of them (27%) still consider it important for students to spend time working problems on their own. HQ22 discloses the responders’ choice to include student activities into lectures and recitations. The responses to this question are somewhat in conflict with the responses to HQ19 and HQ20. On the one hand, about 50% of the responders adopt teacher-centered classes, yet here there appears to be more than 50% support for student-centered class activities. Perhaps the question was poorly posed as it refers both to lectures and recitations.

Table 7

Statistics and response distributions of the received responses to the position questions of the “How” survey, Part E: Your position on adaptation of teaching methods.

Question	Question statement	Ave	STD	Histograms
HQ23	I regularly investigate the engineering education literature	3.63	0.94	
HQ24	It is important that I increase my use of real-world situations	4.12	0.87	
The surprising response to HQ23 indicates relative support for keeping in touch with state-of-the-art engineering education literature, while HQ24 indicates strong support for increasing use of real-world situations in the classroom.				
HQ25	Most important barriers for me to innovate in my teaching role	65%	46%	32%
		Time taken away from research activities	Lack of available institutional funding	Student dissatisfaction with new methods

materials and with class activity (Lewin and Barzilai, 2022).

More work should follow on the investigation of the real PSE needs from the demand side and the users. It is believed that this will provide a much more complete insight on where we should go. Furthermore, the accommodation of new PSE applications – expansion in the great social challenges will further enhance its role and contribution amongst industry and society in general. This paper advocates a change in teaching practice of PSE – from teacher-centered to student-centered instruction. It is worthwhile to consider moving much of the teaching materials from the lecture room to an online setting and require students to cover these materials on their own in preparation for class and tutorial activities. The effort is worthwhile in the long run, as better-prepared students will learn more effectively with the instructors and teaching assistants (TAs), especially if they are expected to take an active part in the problem-solving sessions in class. The paper has provided evidence of the outcome improvements that can be expected.

The surveys have disclosed that there is a gap between the technological capabilities that can be harnessed to the teaching of PSE and practice for many of the responders, most of whom see this as a burden since research time is sacrificed to perform this activity. Perhaps additional incentives are required to promote the move to more active teaching. In this regard, the study of perceptions of Australian engineering academics presented by Knight et al. (2016) suggests a bottom-up strategy for change, driven by awareness of educational goals for students. In conclusion, the objectives of our studies are to provide information and suggestions to improve learning outcomes (i.e., the “What”) but also the best design of student learning environments and practices (i.e., the “How”). The process systems engineering community needs to openly share best practices and resources, otherwise we will be back talking on this subject in 5- or 10-years’ time (Cameron and Lewin, 2009; Cameron et al., 2019; Kiss and Grievink, 2020).

Author contribution statement

All of the authors contributed to the generation of the ideas presented in the paper.

The manuscript was written by Daniel R. Lewin and Emilia M. Kondili.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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