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Agile Process Systems Engineering (PSE) education – 1. What should be taught to achieve desired outcomes mastery by graduates?

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Abstract

Our two-part paper investigates the current status and future trends and suggests a framework for teaching of Process Systems Engineering (PSE) topics that addresses *what* should be taught and *how* these topics should be taught effectively in a classroom setting. This first part concerns the "what" – i.e., which specific key PSE topics should constitute the core requirement of chemical engineering education – either a BSc, but in many cases, an MSc, 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.

Keywords: PSE education, curriculum, active learning

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. The field of Process Systems Engineering (PSE) in the context of Chemical Engineering (CE) 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 modelling, design and control. Subsequently, a large number of academics and researchers have made significant developments and contributions to advance and expand PSE principles in many directions. Recently the interest in PSE education has increased with the development of comprehensive works, as described in Section 2.

Several inspiring works have been recently published that highlight prospects and critical points that need attention for the future of PSE education. 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. 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 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 more contribution. It supports the ideas in play and takes the discussion one step further. The methodology that has been followed in the present paper consist of: (a) a comprehensive survey of the actual topics and application areas covered in the courses taught in academia, and (b) an online survey that received responses from PSE stakeholders around the world (developers, researchers, and management) that map the education perceptions of PSE.

2. Current Status and Contents 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 industrials to cooperate (e.g. forms of industry – academia cooperation, e.g. in Imperial College), 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 modelling, simulation as well as in process optimization. While it has been widely recognized that process integration is key for the successful operation of chemical systems (Baldea and Harjunkoski, 2014), this aspect is still missing in most of the chemical engineering curriculums, i.e., offer courses that integrate fundamental PSE tasks such as process design, control, scheduling and planning strategies.

In a few universities, PSE focused postgraduate studies are also carried out in dedicated MSc Courses, also including research dissertations in the PSE field. These PSE dedicated MSc courses have started appearing in universities programs during the last decade, clearly revealing the strong interest in the field and its expansion in other areas. 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 modelling in 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, modelling of biological systems, advanced bioprocess engineering, multivariate statistics in CE. These courses are found mainly in postgraduate courses since the capacity of undergraduate courses is usually limited to more basic subjects.

3. Survey Content and Methodology

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 respondents 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 second part of our contribution analyses the methods and tools (the HOW issues) to educate engineers more efficiently to respond to present and future needs (Lewin et al, 2022 The “WHAT” survey consisted of 16 questions and was organized into three main categories:

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

To collect as many responses as possible, we reached out to the following communities: the EFCE CAPE Working Party members, EURECHA members, the Energy Section of the EFCE, the AIChE CAST 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 respondents 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 5,000 employees, with a further 25% from large organizations (500-5,000).

4. Survey Results

The responses to the 16 questions establishing the positions of respondents 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.

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.

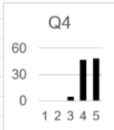
Question	Question statement	Ave	STD	Histogram
Q4	To what extent do you consider PSE skills as useful in developing a career as a chemical engineer?	4.42	0.62	
Not surprisingly, given the PSE-related organizations who were polled, 94% of the respondents considered PSE skills as either important or vitally important to developing a career in chemical engineering. Some respondents 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)*				

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.

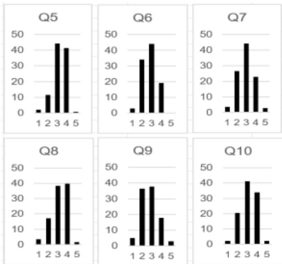
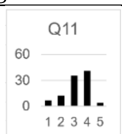
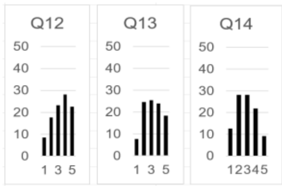
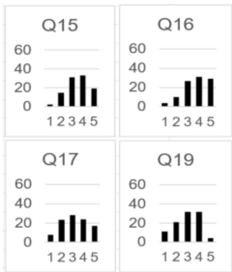
Question	Question statement	Ave	STD	Histogram
How close to your expectations are the skills of freshly-graduated chemical engineers in the following areas:				
Q5	Fundamentals of chemical engineering	3.27	0.76	
Q6	Practical engineering design capabilities	2.79	0.78	
Q7	Critical thinking	2.95	0.87	
Q8	Mastery of process analysis and synthesis software packages	3.18	0.86	
Q9	Computer programming skills	2.77	0.90	
Q10	Professional and personal skills (group work, presentation, writing)	3.13	0.84	
The last question in this part of the survey refers to the impact of teaching innovations on skills				
Q11	Do you see a positive effect of innovative teaching methods on the capabilities of freshly-graduated chemical engineers?	3.23	0.97	

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:				
Q12	Enhancing sustainability or addressing climate change	3.39	1.25	
Q13	Production planning, scheduling or supply chain management	3.20	1.22	
Q14	Safety and risk management	2.87	1.17	
Perceived value of PSE				
Q15	How do you value of PSE in driving business?	3.52	1.03	
Q16	Extent of in-house capability to conduct PSE projects	3.72	1.09	
Q17	Degree of in-house development or implementation of Industry 4.0 projects	3.19	1.20	
Q19	Would you consider bringing in experts from outside to address PSE-related questions?	2.96	1.07	

5. Discussion of the 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 respondents 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 respondents (94%) believe that PSE is a key factor that contributes to the knowledge and capabilities of freshly graduated chemical engineers. The respondents certainly are PSE experts or with PSE knowledge and this affects the survey's outcome. But the general opinion is that young graduates appear to be rather moderate 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 respondents that they have been using PSE methods and tools to face climate change and sustainability issues but to a lesser extent, supply chain management and planning/scheduling problems. In general, PSE is considered very important for their activities, and they are much interested in hiring specialised graduates to accomplish the 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 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 to the engineering core of each curriculum.

To perform successfully, the chemical engineer must be able to design, analyse, operate 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 modelling 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 straight from the beginning in the Chemical Engineering curriculum.

6. Conclusions

Our two-part contribution suggests 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. This first part presents surveys of current practice and the perceptions of practitioners in both academia and industry, concerning the appropriate content of PSE education that would provide prospects and professional advancement to graduates as well as significant added value to industry for the most sustainable solution of 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. Following the principal conclusion of Part 2 of this contribution, which refers to active learning enabled by novel teaching methods, 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.

More work should follow on the investigation of the real PSE needs from the side of the demand and the users. It is believed that this will provide a much more complete insight 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.

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