Advanced Chemical Engineering Professional Skills – Do We Teach Them Effectively?

Fernando Russo Abegão[1], Jarka Glassey[1,*]

[1]School of Engineering, Newcastle University, Newcastle Upon Tyne, United Kingdom

Abstract: Chemical engineering professional skills are essential in ensuring that the graduates are able to effectively face not only the current, but also future societal and technological challenges. Whilst the core chemical engineering knowledge in unit operations, such as reaction engineering and separations, remains a defining feature and a fundamental requirement of various accreditation criteria of the chemical engineering courses, it is clear that this in itself is not sufficient to provide the future generations of chemical engineers with the knowledge and skills to address the challenges they will face in their future professional careers. An important part of this skill set is the ability to deal with uncertainty, to innovate, to represent a conceptual model of a process or a unit operation in such a way that it allows the user to explore the response of the process / unit operation to dynamic disturbances and to optimise the performance of the given process / unit operation. At Newcastle University this forms the basis of the advanced design task presented in this contribution. Following a brief international review of the importance of core chemical engineering knowledge and skills (gathered by the authors during the recent EU sponsored iTeach project), the learning outcomes and the structure of the revised advanced design module will be presented. The emphasis will be placed on the assessment of critical professional skills as outlined above, indicating various approaches taken to ensure a broad professional skill set development.

Keywords; advanced chemical engineering design, innovation, assessment, conceptual understanding, dynamic modelling.

**Correspondence to: Jarka Glassey, Merz Court, School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom, E-mail: jarka.glassey@ncl.ac.uk*

1. INTRODUCTION

Rapid technological advances place increasing challenges on the skill sets of the chemical engineering students and graduates. Whilst arguably the chemical engineering profession has changed significantly when compared to the knowledge and skills required at the stages of the inception of the profession in late 1800s (Perkins, 2003), the rate of change is undoubtedly increasing, even more rapidly in the last few decades. It is thus important that chemical engineering graduates are not only secure in their knowledge of core chemical engineering concepts, but are able to apply this in innovative problem solving, conceptual design and solutions of societal challenges in the context of limited information or uncertainty. Sharples *et* al. (2016) argue that ‘preparing learners to be future-ready requires learning approaches that teach students to be responsible citizens, contributors and innovators, equipping them with agency and autonomy in planning what and how to learn, and helping them to develop cultural and interpersonal understanding.’

Yet, the chemical engineering curricula tended to concentrate on the more easily delivered and assessed core knowledge, although increasingly scholarly literature reports alternative pedagogical approaches supporting active learning, and aiming to develop not only core technical knowledge, but also important professional competencies (e.g. Munir, *et al.* 2018, Li and Huang, 2017. Promentilla *et al* 2017, Roach, 2014, Liu and Stengel, 2011). An effective means to develop and assess this knowledge and competencies within chemical engineering formation is through process and product design, often with the use of process simulation tools (e.g. Rodriguez and Cussler, 2016, Belton, 2016, Komulainen *et al*, 2012).

This contribution demonstrates the perceived significance of the professional competencies by the academic, industrial and recent graduate stakeholders, as identified within the EU sponsored iTeach project. Subsequently, details of the revised advanced design project course at Newcastle University are described, setting out the intended learning outcomes of the course, the mode of delivery and placing particular emphasis on various modes of formative and summative assessment designed to support student learning and the acquisition of critical skills and competencies.

2. ASSESSING THE IMPORTANCE OF CHEMICAL ENGINEERING LEARNING OUTCOMES RELATED WITH PROFESSIONAL SKILLS

2.1 Methodology

A framework of chemical engineering learning outcomes was developed as part of an international collaboration project (iTeach), which is outlined in more detail by Glassey et al. (2018). In this framework, in addition to Maths, Science, and Core Chemical Engineering learning outcomes, three sets of professional skills were identified: (1) Engineering practice and design, (2) Advanced Level, (3) Embedded Learning.

The importance of these learning outcomes was assessed through an international survey, mostly focused on European countries. The survey was distributed via the consortium members networks among three interest groups: academics, graduates and employers, which were asked to rate the importance of a list of attributes for each set of learning outcomes. Academics were asked to rate the importance of the attributes in the graduates' careers after graduation, graduates were asked to rate the importance of the attributes for their careers, and employers were asked to rate the importance of these attributes in graduates for their business. A Likert-type scale was used with 5 categories of importance scored accordingly: "1- Not at all important", "2-Somewhat important", "3-Neutral", "4-Important" and "5-Very important".

Data was anonymised, and a statistical analysis was carried out using Minitab. Average scores were determined for each attribute and the confidence intervals of the mean were established with 95% confidence.

2.2 Results and Discussion

The results of the survey are summarised in figure 1, shown grouped by set of Learning outcomes (Engineering Practice and Design, Advanced Level and Embedded Learning). For each individual outcome within each set, the scores for academics, graduates and employers are shown side by side for ease of comparison.

Figure 1 shows that most learning outcomes are considered as important (4) or very important (5) by most groups surveyed, which can possibly be justified by the fact that the development of the framework has been informed by multiple professional accreditation requirements in an attempt to capture all aspects of tertiary education that could be deemed important and relevant for further validation. The highest importance ratings and good agreement between all surveyed groups were particularly noticeable for Embedded Learning outcomes (figure 1 (c)), which comprise mostly general professional skills, such as: problem solving skills, communication skills, working effectively with others, leadership skills, effective use of IT, project planning and time management, and continuous professional development (CPD). These skills are cross-cutting across all chemical engineering subject areas, and therefore more likely to be considered important by a wider range of stakeholders. It is also noticeable that there is a small differentiation between the first three embedded learning skills listed above and the last four.

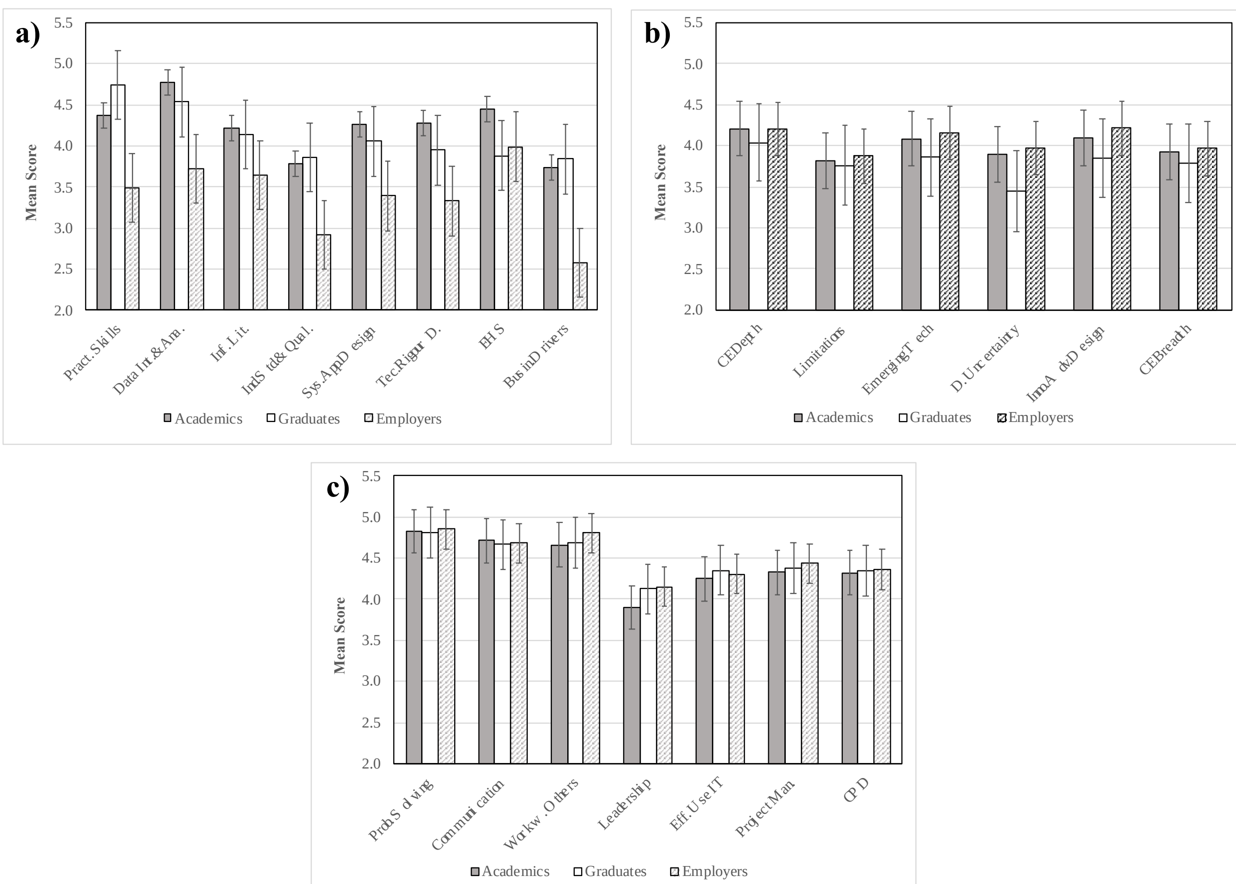

Figure 1 Mean importance scores for the learning outcomes related with (a) Engineering Practice and Design (b) Advanced Level and (c) Embedded Learning. The error bars show the 95% confidence intervals for the mean.

However, there are exceptions (some learning outcomes scored below important (4)), and for some learning outcomes it is also possible to notice some differences between importance ratings attributed by each group surveyed.

Figure 1 (b) focusses on Advanced Level learning outcomes, namely: chemical engineering science depth, limitations of current engineering practice, awareness of emerging technologies, design in the context of uncertainty, innovative advanced design, and chemical engineering science breadth. All learning outcomes in this set had a mean score of important (4), with some tendency for graduates to rate these slightly lower, and with a wider spread of ratings, while there was excellent agreement between the mean and spread of the ratings from academics and employers. These small differences could possibly be justified by the lower professional experience of graduates and more limited experience in workplace.

Engineering practice and design skills ratings are shown in figure 1 (c). These include: practical skills, data interpretation and analysis, information literacy, industrial standards and quality assurance, systems approach to design, technical rigor in design, awareness of safety, health and environment issues (SHE), and awareness of business drivers. It is possible to see that while academics and graduates rate all these learning outcomes as important (4) or very important (5), employers' ratings are far below, mostly distributed around neutral (3), but spreading from somewhat important (2) to important (4) depending on the specific learning outcome.

The fact that quite a few of these outcomes are closely related to design or to engineering practice modules taught in most universities explains why academics and graduates rate highly the importance of these learning outcomes. On the other hand, most chemical industry employers will focus on production rather than design, and not all industries will have the same requirements in terms of engineering practice skills, which could justify the lower importance ratings awarded by the employers in comparison with the ratings awarded by academics and graduates. Together with the more limited work experience of the graduates, this could also explain the higher spread of answers shown by a wider confidence interval for the mean.

Perhaps more surprising is the fact that practical skills, industrial standards and quality, and awareness of business drivers are rated relatively low by employers. However, most companies tend to invest heavily in new graduates training, and most often the specific practical skills are acquired on the job, while business and market awareness specific are often briefed in early career training programmes. Additionally, investment in standards and quality is usually dictated by regulatory and compliance restrictions or by fast return on profits (e.g. implementation of 6-sigma and kaizen systems) and this is another area where companies often invest in specific training.

3. ADVANCED DESIGN PROJECT COURSE

In order to develop advanced engineering design practice skills, Newcastle University chemical engineering (CE) curriculum contained an advanced design module for a number of years. The core task for the students was to develop their detailed CE unit operation design from the previous year's design project task and explore the dynamic behaviour of the unit under a realistic set of scenarios. Matlab-based simulation models, written by the students individually during the module, provided the means for this investigation and the assessment was based on: 1) a scoping document submitted in the first part of the course, setting out the characteristics of the system, the model and the scenarios; 2) a final report on the dynamic responses of the system.

3.1 Revised course structure

The previous format of the course was providing students with very important professional competencies, although a number of challenges were identified over the years of operation. Increasing student cohort size led to increasing stress on the delivery, support and the marking of the course outcomes and impacted the student satisfaction. It was also more challenging for the students to individually develop functional Matlab models of required complexity and robustness to perform the simulations. Despite the academic course team increasing to four, it was still challenging to support the diversity of the unit operations and the programming complexities.

In 2017 it was decided to revise the course and to review the alignment of the intended learning outcomes (ILOs) with the assessment methods, to provide more formative feedback and support to students and to include peer-assisted learning and peer evaluation. It was decided to limit the extent of the computer simulation to a reactor, but extend the learning to a conceptual analysis of individual unit operations students designed in their previous design project.

With this aim in mind the ILOs shown in Table 1 have been agreed by the academic team of five chemical engineering educators:

Table 1: Intended learning outcomes of the advanced design project course.

Intended Leaning outcomes
Intended Knowledge Outcomes ***Students should be able to:*** ***• Acquire a deeper understanding of the dynamic behaviour of unit operations*** ***• Understand and apply this knowledge to more advanced process design.*** ***Intended Skill Outcomes*** ***Students should be able to:*** ***• Construct dynamic models of unit operations and simulate their performance*** ***• Write computer code for the purpose of simulation*** ***• Identify issues within process design that that could be enhanced through dynamics*** ***• Understand the dynamic interaction between chemical and physical systems.***

3.2 Course delivery and assessment

The revised course is 10 ECTS credits, delivered concurrently with other modules in the final stage of an integrated MEng programme. The delivery consisted of 12 scheduled lectures (1 h) with nearly each lecture followed by a 3 h practical session (10 practical sessions in total). During the practical sessions, students worked in groups of 4-6 developing progressively more complex Matlab-representations of a reactor behaviour under various scenarios. During each lab session students expanded on the concept covered in the preceding lecture and developed code with specific features. At the end of the practical, each student uploaded the developed piece of code onto Blackboard, which was used as Virtual Learning Environement (VLE) demonstrating the code functionality. This was then evaluated by the academic team before the next practical (maximum of 2 marks available for each practical based on the quality of coding, i.e. 20% of the overall module mark).

Each group selected a specific process and a kinetic model they wished to explore (often related to their process design tasks, ranging from complex chemical synthesis, polymer or various bioproducts manufacture). The topics were selected upon consultation with the lecturers, and extensive feedback from the academic team through the VLE discussion board forum was provided, keeping it visible to all students so that all groups can learn from the feedback on common points. After 10 weeks of the course, the groups submitted their Matlab code capable of simulating the behaviour of the reactor under standard conditions and providing the framework for testing various dynamic scenarios. Each group also prepared a presentation (typically pre-recorded audio presentation with slides and demonstration of the code functionality) which was submitted on the VLE. The academic team reviewed the presentations and, during a dedicated computing lab session, they had the opportunity to question the students on various aspects of the presentation, providing a summative evaluation of the presentation. Students were also asked to peer evaluate the contribution of each member of the group to the code development and this evaluation was used to weight the individual mark for each student for this part of the course (20% of the total module mark). Subsequently, a detailed formative feedback on the code, reviewed independently by two academics, was provided to each group.

In the second semester, students worked individually on exploring the selected dynamic scenarios for their reactor and produced the final report. This report consisted of a group component (5 pages) setting out the details of the modelled process kinetics, the constraints and assumptions, and the approach taken to test the realistic behaviour of the resulting simulation model. Each student then described their own dynamic investigations (5 pages each), justifying the selected scenario and the tested ranges and critically analysing the dynamic behaviour of the system. Each student also produced a one-page analysis of how learning from this task could be used to develop a conceptual model of a different unit operation (typically that used by a student in their detailed plant design task) and how this could be developed into a simulation model enabling the exploration of the dynamic response of such a unit to a range of realistic scenarios. The final report was independently marked by two academics against the agreed marking criteria, which were clearly communicated to the student. A moderation meeting of the course team then provided a final quality check in terms of marking and feedback. The mark for the report represented 50% of the module mark (with 35% of the total module mark individually attributed to group members). The final 10% of the module mark were attributed to the final code quality.

3.3 Course evaluation

Regular interaction of the course team with the students during the practical sessions provided a useful opportunity to check the progress of the students. The end-of-semester evaluation also provided a valuable check-point on progress half-way through the course. Compared to previous years, when students expressed concerns over the level of stress and confusion around the coding in particular, this year the evaluation was much more positive (overall satisfaction with the module scoring 3.9 and intellectual stimulation 4.1 out of 5 at this stage, 54.4% response rate).

The free text comments in particular highlighted the appreciation of students' learning essential professional skills (Table 2).

Table 2. Student evaluation comments.

Student comments
Best feature of the module: • ***Assessed labs (gaining marks as an incentive to learn)*** • ***Clear coding, well structured, lab sessions really helpful.*** • ***Great structure and varied methods of assessment*** • ***Group work.*** • ***I like how there were multiple lecturers in the lab to help. I found MATLAB hard so having multiple lecturers there to help was very beneficial.*** • ***Initially quite challenging, sense of achievement once understanding is achieved*** • ***It is taken step by step building from the bottom up rather than throwing you straight in at the deep end.*** • ***Lab classes really helpful, helped me to understand about Matlab and what we need to do, helped me to stay on task.*** • ***Using software to design chemical equipment is the best highlight of this module.***

The moderation meeting of academic staff following the final report marking also provided a valuable opportunity for staff to review the improvements of the module and discuss further refinements. Overall a much greater understanding of Matlab coding and some excellent examples of understanding of the process dynamic responses were observed, with detailed (multiobjective) reactor optimisation. Understanding of system behaviour under dynamic conditions, in the absence of detailed information and with high level of uncertainty as well as team-working, time management and critical self- and peer evaluation were noted amongst others. Whilst the practical sessions were generally praised by the students, the time consuming nature of marking led the team to proposing modification for next year in this aspect.

4. CONCLUSIONS

This contribution demonstrated the general agreement of academics, employers and graduate in their perceptions of the importance of various aspects of advanced chemical engineering knowledge, practice and skills. The described advanced design course provided and ideal opportunity to develop a number of these critical skills and support the self-learning of students, which represents an important aspect of future-ready professional chemical engineers as argued by the authors.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contribution of Dr C O'Malley, Dr M Mijajlovic, Dr D Ofiteru and Dr M Willis in the design, delivery and evaluation of the advanced design module. The project "Improving of Teaching Effectiveness in Chemical Engineering" (ITEACH), Project No. 539959-LLP-1-2013-1-UK-ERASMUS-EQR, was funded by the Life Long Learning

Programme Erasmus Multilateral projects programme. The contribution of all the iTeach project partners and survey respondents is also gratefully acknowledged.

6. REFERENCES

Belton, D.J. 2016. Teaching process simulation using video-enhanced and discovery/inquiry-based learning: Methodology and analysis within a theoretical framework for skill acquisition, *ECE*, 17, 54-64

Glassey, J et al. (2018) Chemical Engineering Education – European Perspective Part I – Academic Perceptions of Learning Outcomes and Methods of Delivery, *In preparation or submission to Chemical Engineering Education*

Komulainen, T.M., Enemark-Rasmussen, R., Sin, G., Fletcher, J.P., Cameron, D. 2012. Experiences on dynamic simulation software in chemical engineering education, *ECE*, 7, e153-e162

Li, X., Huang, Z. 2017. An inverted classroom approach to educate MATLAB in chemical process control, *ECE*, 19, 1-12.

Liu, W.C., Stengel, D. N. 2011. Improving student retention and performance in quantitative courses using clickers. *Int J Tech Mathematics Education*, 18 (1), 51–58.

Munir, M.T., Baroutian, S., Young, B.R., Carter, S. 2018. Flipped classroom with cooperative learning as a cornerstone, *ECE*, https://doi.org/10.1016/j.ece.2018.05.001.

Promentilla, M.A.B., Lucas, R.I.G., Aviso, K.B., Tan, R.R. 2017. Problem-based learning of process systems engineering and process integration concepts with metacognitive strategies: The case of P-graphs for polygeneration systems. *Appl Thermal Engng*, 127, 1317-1325

Roach, T. 2014. Student perceptions toward flipped learning: New methods to increase interaction and active learning in economics, *Int Review Economics Education*, 17, 74-84

Rodriguez, A., Cussler, E.L., 2016. Teaching chemical product design, *ECE*, 14, 43-48.

Sharples, M., de Roock , R., Ferguson, R., Gaved, M., Herodotou, C., Koh, E., Kukulska-Hulme, A., Looi, C-K, McAndrew, P., Rienties, B., Weller, M., Wong, L. H. 2016. *Innovating Pedagogy 2016:* Open University Innovation Report 5. Milton Keynes: The Open University.