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Teaching chemical engineering in Europe – developments, dilemmas and practical examples

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Dedicated to the memory of Professor Jerzy Bałdyga

This perspective paper focuses on the changes in teaching chemical engineering in Europe triggered by new challenges and megatrends observed in the chemical and related industries. Among the new teaching areas to address those challenges and megatrends, process intensification, digitalization and advanced materials are expected to play the most important role and are discussed in more detail. The discussion on incorporation of those new areas in the university curricula is illustrated with a comparison of educational approaches to the chemical engineering teaching at two universities – Delft University of Technology and Warsaw University of Technology. The aim of this paper is to focus the attention of university teachers and potential decision makers on the most important challenges for contemporary teaching of chemical engineering.

Keywords: teaching of chemical engineering, teaching dilemmas, challenges and megatrends in teaching

1. INTRODUCTION

Chemical engineering has been changing throughout the years and so has been changing its teaching as a scientific discipline. Originally based on the "unit operations" paradigm initiated by Arthur D. Little and presented for the first time in the famous *Principles of Chemical Engineering* textbook by Walker et al. (1923), it focused primarily on studying the major equipment for chemical manufacturing, including its construction and performance. Consequently, chemical engineering teaching until 1960's included a heavy mechanical engineering component and had often been offered by mechanical engineering faculties. In the early 1960s, this unit operation paradigm was largely replaced by the "transport phenomena" paradigm marked with the publication of the textbook *Transport Phenomena* by Bird et al. (1960). That new paradigm brought important changes into university curricula. Momentum, heat and mass transfer became core topics, accompanied by mathematical modelling and simulations thanks to the fast development in computational infrastructure. Further developments that occurred in the last decennium of 20th and the first

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two decennia of 21st century, with rapid growth of interest in bio-based processes, biomedical engineering and nanotechnologies, have introduced again significant changes in the profiles, and even in the names of former chemical engineering departments.

With university teaching restricted to a maximum of five years for the BSc and MSc levels together, the main problem in teaching chemical engineering (and of course in any other educational process) is related to the following fundamental dilemmas: "*what to teach?*", "*what depth to teach?*", "*when to teach?*" and "*how to teach?*". A solution of this problem is not a trivial one as the challenges are continuously changing due to the rapid changes in technology, science and society worldwide.

Chemical and related industries remain the primary destination of university graduates of chemical engineering and when talking to the industry about what kind of knowledge and skills the graduates they recruit should possess, one often hears: "teach them good fundamentals, the rest they will learn within the company; do not teach them your research hobbies". Yet, the same industries are facing various global challenges and megatrends that will change and define their profiles and activities in the coming decades. Think of sustainability-related challenges, such as decarbonisation, electrification or circular economy. Think of "Industry 4.0" with its digitalisation – Artificial Intelligence, machine learning or robot-assisted processing. Think of new, advanced materials (e.g. for medical applications) and the related new manufacturing approaches, such as 3D-printing, or about distributed manufacturing in modular plants with remote control.

Does the academia have to anticipate all those upcoming developments in chemical industries and adapt the teaching curricula in chemical engineering accordingly? And how? In this paper we will enlighten and discuss some paths that might be worth following.

2. TEACHING DILEMMAS

The activities of the European Federation of Chemical Engineering Working Party on Education (EFCE WPE) have been helping over decades to identify effective solutions for education in chemical engineering at European universities. Therefore, before starting considerations on the future of education in chemical engineering, a short survey of its previous decisions, studies and achievements within this field should be summarised.

The fundamental paper *The education of chemical engineering in the third millennium* (Gillet, 2000a) written at the beginning of the third millennium under the auspices of EFCE WPE indicated the challenges for chemical engineering education and particularly dealt with how to implement the elements of sustainable development, which has been broadly introduced in that period. In the above paper, the results of 1994 WPE survey of chemical engineering curricula in European universities have been discussed, in order to identify a core curriculum and provide guidance on what to teach chemical engineers at the first degree level. The summary report on the chemical engineering core curriculum, compiled by J.E. Gillett from the report by J. Tracez to the Scientific Committee of the EFCE in 1994 and updated in 2000, can also be found in his subsequent papers (Gillett, 2000b; Gillett, 2001). That "core curriculum" representing about 50% of all courses given in Europe, has been suggested as a common objective to all chemical engineering programmes at European universities. Such a curriculum is particularly important for the European Union, where a professional title "chemical engineer" should correspond to a similar type of education and competence in all Member States, while the existing teaching programmes had been covering a wide range of different profiles (Tracez, 1994, Pohorecki and Szebenyi, 1997). However, the core curriculum should be seen as a guideline only, not as an obligatory recommendation to be followed at all universities.

The first-degree curriculum can be divided into three major parts:

- basic science (mathematics, computer use, physics and chemistry),
- engineering core (thermodynamics, physical chemistry, fluid mechanics, transport phenomena, unit operations, chemical reaction engineering, plant design, equipment, materials, process dynamic and control, chemical engineering laboratory, safety and environment),
- electives (in depth studies of special subjects).

Since its introduction, the European Union's Bologna Declaration (EFCE, 1999) which introduced three levels into the education programme (BSc, MSc and PhD), became a new European challenge in higher education. The European Federation of Chemical Engineering (EFCE) very fast decided about its attitude towards the Bologna Process, then during the next years the Working Party on Education of the EFCE published several papers and statements, e.g. Molzahn (2004), EFCE (2005, 2010, 2020), Pohorecki (2003). The last one successively updated became the official EFCE document, called the *EFCE Bologna Recommendations*, which is now a much-used guideline for shaping chemical engineering degree programmes and harmonising higher education in Europe. EFCE welcomed and supported the aims of the Bologna Declaration and the main purpose the EFCE's recommendations is to ensure that graduates who have completed a chemical degree possess the skills required for chemical engineering practice. This includes knowledge of fundamentals but also competences beyond engineering science – e.g. working in teams and across borders. Times change very fast, so the need to adapt now is as great as ever – it is enough to mention globalization, digitalization and last but not least the experience resulting from the COVID-19 pandemic and an unprecedented demand for social distancing – see EFCE Bologna Recommendations 2020 (EFCE, 2020). Therefore, along with the usual dilemma "*what to teach?"* and "*how deep to teach?*" special emphasis should nowadays be put on the question "*how to teach?*", as the *on-line* teaching, including even virtual or/and remote laboratory classes, became the method almost equivalent to traditional ones.

3. NEW TEACHING AREAS TO ADDRESS CURRENT AND EXPECTED DEVELOPMENTS

3.1. Sustainability, electrification and Process Intensification

Sustainability is the leitmotif in teaching Process Intensification (PI). The first MSc-level courses on PI started in 2003 at Delft University of Technology, and meanwhile have been introduced in a number of other universities (Fernandez Rivas et al., 2020a; Fernandez Rivas et al., 2020b). The current teaching of Process Intensification according to the Delft methodology supported by the recently published textbook (Stankiewicz et al. 2019) links PI directly with primary challenges of sustainable development, such as decarbonisation and the use of renewable electricity, lean energy processing, material efficiency and waste minimization. During the course students get familiar with the four elementary PI-domains in equipment and process design: spatial, thermodynamic, functional and temporal (Fig. 1).

In the spatial domain students are taught the benefits in terms of process efficiency resulting from the elimination or minimization of randomness inside the processing equipment space via the application of structures. Structures at various scales are presented and discussed, starting from nanostructures addressing molecular interactions (e.g. nanostructured catalysts, molecular reactors), through structures addressing heat transfer (e.g. microchannel heat exchangers and reactors, millireactors, plate heat exchangers), structures addressing mass transfer (e.g. structured packings and catalysts), to structures addressing mixing and fluid flow (e.g. micromixers, static mixers, fractal distributors). Consequently, issues related to modularization and modular plant design are discussed in this part of the course.

In the thermodynamic domain the use of various energy forms and transfer mechanisms is explained, including the energy of electric and magnetic fields (e.g. microwaves, plasmas, UV), energy of flow (e.g.

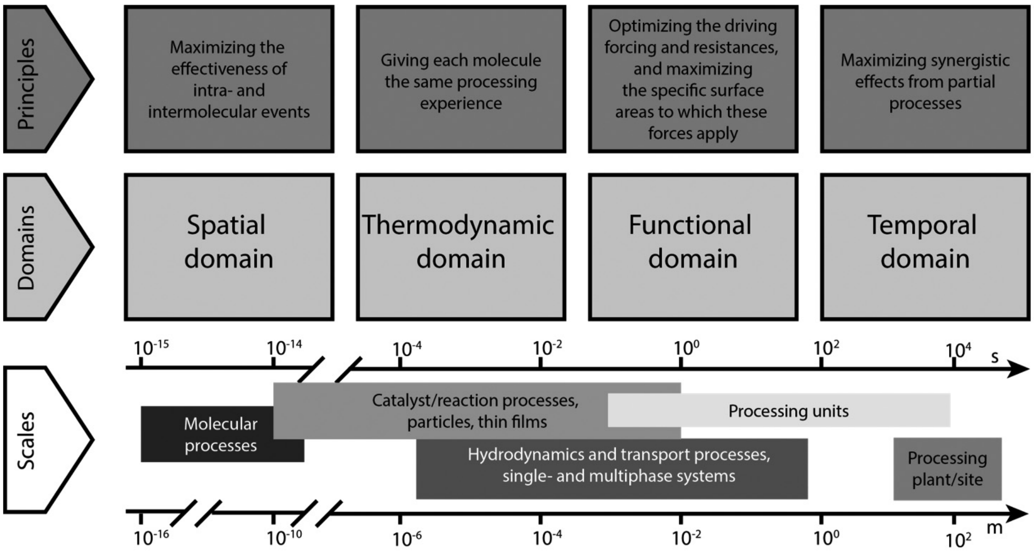

Fig. 1. Principles, domains and scales of Process Intensification. Adapted with permission from Van Gerven and Stankiewicz (2009). Copyright (2009), American Chemical Society

in ejector or impinging-stream systems) and the energy of rotation (e.g. in rotating packed beds and spinning disc or rotor-stator reactors). An important element discussed here is the concept of a future chemical processing plant using renewable electricity as a primary energy source. This includes also the related issues such as renewable electricity generation, short- and long-term energy storage and recovery, control of renewable electricity-based processes, or region-dependent plant design.

Synergy is the keyword in the functional domain and students are taught how to combine different functions within one process step or equipment, in order to achieve a synergistic overall effect. Heat-integrated reactors, reactive separations and hybrid separations are the most important categories of functionally integrated operations discussed here. Again, sustainability-related benefits including higher product yields and lower energy consumption in downstream processing are shown for each of the technologies. On the other hand, the pitfalls and constraints of functional integration related to the loss of degrees of freedom and to the existence and size of the operational feasibility window, as well as the ways of dealing with them are discussed.

Finally, in the temporal domain, the methods of manipulating the duration/characteristic times of events and the purposeful introduction of dynamics (periodicity, oscillations) in process systems are reviewed. An important element in this part is the switch from batch to continuous, oriented towards efficiency boost and waste minimization in pharmaceutical and fine chemical processes conventionally run in the batch mode.

The lectures on Process Intensification in Delft are followed by a case-study project, in which student teams are requested to conceptually re-design a processing plant using PI approaches and technologies learned in the first part of the course, in order to make the process safer and more environment-friendly. During the introduction to the case-study students are additionally familiarized with the basics of Inherently Safer Process Design. Re-designing the infamous Union Carbide's Bhopal carbaryl plant or Flixborough cyclohexane oxidation plant serve here as standard assignments.

3.2. Digitalization

A significant role of digitalization in the contemporary world, and therefore also in the chemical industry as well as its impact on chemical engineering profession and education is highlighted in the recent excellent review by Feise and Schaer (2021). First, for clarity their explanation of fundamental difference between digitization and digitalization is worth mentioning. Digitization is just performing something in a digital space or transforming any process from an analogue to a digital format (a good example are digitally taken and stored images), while digitalization is an operation with digital data.

Digitalization transforms the chemical industry very fast and covers the entire activity related to production, logistic as well as the connection with suppliers and customers. Feise and Schaer start the discussion about the impact of digitalization on teaching and learning chemical engineering presenting a milestone in the approach to education in the digitized world – i.e., five theses developed at the 57th Tutzing Symposium (2018):

- knowledge of fundamentals remains indispensable even in digital era,
- digitalization requires continuous evaluation and reconstruction of curricula,
- development of a demand-oriented education system for the digital age,
- digitalization enforces life-long learning,
- digitalization requires better interaction and communication skills.

Then, discussing the content of new teaching programs that would prepare students for the digital era, they refer to six areas of competencies indicated in the EFCE Bologna Recommendations (EFCE, 2020):

- knowledge and understanding,
- engineering analysis,
- engineering design,
- investigations,
- engineering practice,
- transferable skills,
- making judgment (social, ethical, technical, and financial aspects),
- communication and teamwork,
- life-long learning.

Finally, Feise and Schaer conclude with recommendations concerning the teaching content in the digital age. These can be summarized as follows:

- numerical methods are becoming increasingly important, so future engineers should be familiar with commercial codes, but also able to develop new ones,
- artificial intelligence can help to adapt and optimize processes in real time, so there is a need for graduates to know the appropriate tools,
- future engineers have to train themselves throughout life to follow changes,
- chemical engineering discipline still expands to new fields, so graduates have to be able to extend methods and tools of chemical engineering to these new areas,
- communication, critical analysis, team work and problem solving are necessary in the contemporary world, so they have to be continuously practiced and improved.

An important aspect of digitalization is that it can be creatively utilized for development of chemical engineering tools and methods. For example, due to progressive digitalization of chemical industry (called Industry 4.0) a huge number of data acquisition systems collect experimental data taken from huge numbers of processes, units, and plants. Formerly, those data were used exclusively for the documentation of the process history. However, they contain a lot of useful information, often quite hidden, because paradoxically the more data are registered the harder is their direct legibility. That hidden information can be extracted, for example, using artificial neural networks (ANN), as models based on ANN exhibit the rule-following behaviour without containing any explicit representation of those rules (e.g. see Molga, 2003). ANNs and neural models have been known for many years, but nowadays due to digitalization their application can be particularly attractive and efficient, as they can utilize all those collected experimental data. Due to abilities of ANN to approximate any non-linear dependence without explicit knowledge of this dependence they can be particularly useful for data analysis and transformation, process dynamic (control tasks) as well as modelling complex functional dependencies, e.g. unknown kinetics of complex reaction systems (Molga et al., 2000). Artificial Intelligence (AI) based on neural models utilizing collected experimental data can be very helpful for on-line control of very complex systems and processes as well as robot-assisted processing – e.g. see Unnikrishnan et al. (2021) and Christofides (2020–2021). Additionally, ANN can be very useful in advanced modelling, particularly in multiscale modelling, the importance of which increases due to the developments in nanotechnology and a need for modelling processes at the nanoscale level. ANNs make it possible to efficiently transmit the results from the nano-scale to the larger micro and meso-scales – among others see Molga and Westerterp (2013) as well as Xiao and Ni (2021).

Large storage capacity and continuously increasing speed of modern computers is here particularly propitious, also in view of the fact that the number of commercial codes available for neural computations is still growing. The need to include the fundamentals of neural computations in core curricula at both bachelor and master levels has been clearly articulated in the relevant literature, e.g. by Kakkar et al. (2021).

Since March 2020, due to the COVID-19 pandemic, the academic community has been facing extraordinary challenges caused by the immediate shutdown of face-to-face contacts and shift to the on-line learning. It was particularly difficult in case of teaching chemical engineering or even engineering in general, as a quick transformation of traditional teaching laboratories into remotely operated virtual ones was not an easy task. A high level of digitalisation of transformed laboratories proved here indispensable. This relatively fresh phenomenon has already been quite widely described in the literature, for example in the Special Issue of *Education for Chemical Engineers*, where a series of papers entitled Digitalisation in Chemical Education and Training has been published (Liauw et al, 2021). In those papers, among other things, innovative approaches to the on-line teaching are described and discussed, while the presented analysis is usually based on both, teacher observations and student surveys. One of the papers, a review written by Bhute et al. (2021), presents emerging approaches to virtual, remote or combined methods. The value of these approaches was based on such factors as: learning outcomes, availability of resources, used technology, scheduling and cost. The authors highlighted that a positive experience acquired owing to the COVID-19 pandemic should be adapted to everyday "regular" teaching practice and core curricula in the post-pandemic world.

The implementation of practical teaching activities, such as laboratory classes, is the greatest challenge for the on-line learning. Due to the pandemic restrictions, laboratory classes at numerous universities have been carried out either in the form of recordings of laboratory exercises performed by teachers or in the form of live experiments carried out by single students with other team members following the experiments through the Internet. Such forms have enabled active participation of students in practical exercises and the acquisition of intended learning outcomes.

3.3. New advanced materials

Nanoscience and nanotechnology as well as functional materials with tailored properties present one of the fastest growing areas of engineering and technology, having a major impact on global production and economy. During the last decades nanotechnology has expanded and flourished with a wide variety of applications. Also, the functionalization of materials is very often carried out and controlled at the nano-scale. Because of those developments it is essential to include nanotechnology in the educational curricula.

A pioneering approach to the application of chemical engineering principles in the design of nanoscale processes and nanoengineering has been presented in the book by Elnashaie et al. (2015). The book shows from the chemical engineering viewpoint how to integrate the fundamentals of nanotechnology with a detailed explanation of specific nanoscale processes and educates the readers about nanoscale process design, simulation, modelling and optimization.

As an example of introduction of nanotechnology into chemical engineering curriculum we describe hereunder a new track at the second-cycle studies: Nanostructured Product Engineering, lunched in 2019 at Warsaw University of Technology and offered within the School of Advanced Chemical and Material Technologies, a joint initiative of three faculties: Chemical and Process Engineering, Chemistry and Materials Science. As a part of their didactic activities, students use the research infrastructure of the Graphene Laboratory at the Faculty of Chemical and Process Engineering. Due to the convergence of initial knowledge in the areas of engineering and chemical technology and materials engineering, the School also implements an identical program of the first year of full-time first-cycle studies at the three faculties mentioned above, which also rationalizes the teaching activity of the Faculty in the economic context.

Nanostructured Product Engineering track covers the key issues related to nanotechnology. The class *Engineering of Nanocatalysts* provides the basic information on nanocatalysis, preparation and separation methods, on the research of properties and structure of nanocatalysts, as well as on modelling of processes involving nanocatalysts. This class also provides information on the use of nanocatalysts and compares their performance with conventional catalysts. The class *Colloidal System Engineering* teaches the properties of colloids, methods of producing colloidal particles by precipitation and grinding, and the use of colloids. Students also gain knowledge about amphiphilic systems (surfactants), liquid-liquid interfaces and polymer-surfactant and polymer-surface interactions. In the Laboratory for the production of nanostructured materials, students get familiar with the processes for obtaining nanostructures and nanomaterials, which constitute their practical preparation for designing nanotechnological processes. Laboratory exercises include preparation of colloidal CdSe nanocrystals, spectroscopic and electrochemical characteristics of small and high molecular organic semiconductors, characterization and stabilization of colloids, COF (Covalent Organic Frameworks) organic porous materials, synthesis of ceramic nanoparticles by sol-gel method, synthesis and characteristics of quantum dots, quantum graphene preparation, production of polymer composites and research on the removal of heavy metal ions using hydrogels containing graphene oxide. The class *Technologies of Energy Conversion and Accumulation* covers the material and functional aspects of energy accumulation and conversion devices, with particular emphasis on electricity and the growing role of renewable energy sources. The lectures provide information on modern energy sources, the physicochemical foundations of galvanic, fuel and photovoltaic cells, energy conversion and accumulation systems, while the aim of the laboratory exercises is to use the chemistry of functional materials to design and obtain electrodes and electrolytes. As part of the lectures and laboratory practice in the class *Medical Nanotechnology*, students learn theoretical and practical aspects of technologies used in the production and identification of properties of nanotechnology products, such as medical products and drugs for modern medicine. Within the *Material Functionalization Laboratory*, students conduct practical exercises on the synthesis and characterization of Metal-Organic Framework materials, production and characterization of nanocrystalline electrochemical metallic and composite coatings, and testing of catalysts in a formic acid fuel cell (DFAFC). Graduates of the Nanostructured Products Engineering course have detailed knowledge of the design and implementation of nanostructure manufacturing processes useful in the processing industry and medicine. They know the processes for producing nanocatalysts, bone scaffolds, advanced graphene materials and their derivatives. They have the ability to conduct the production processes of advanced nanostructured materials on industrial scale, design such materials and implement their production processes.

Last but not least, it is important to note clear mutual relations between the three new areas presented above: process intensification, digitalization and advanced materials. On the one hand, digitalization plays a crucial role in the discovery and development of new materials, as discussed in the excellent recent review by Kimmig et al. (2021). On the other hand, advanced materials and process intensification are connected by a "Yin-Yang" relation: advanced materials help intensify chemical processes, while process intensification methods allow manufacturing new materials with unique functionalities, as presented by Stankiewicz and Yan (2019).

4. WAY FORWARD

Contemporary trends, significant aspects of research, education and practice as well as perspectives for the future in chemical and biochemical engineering (C&BE) are given in the recent paper prepared by a prominent group of scientists representing academia and industry in Europe – see Gani et al. (2020). This multi-layered view – shown in Fig. 2 – can be very helpful to indicate important issues and provide guidance to meet the grand challenges of this century also with respect to C&BE education. Following the proposed multi-layer concept the authors indicated what skills and knowledge are needed for each level of the education programme (BSc, MSc and PhD) and related their considerations to this concept.

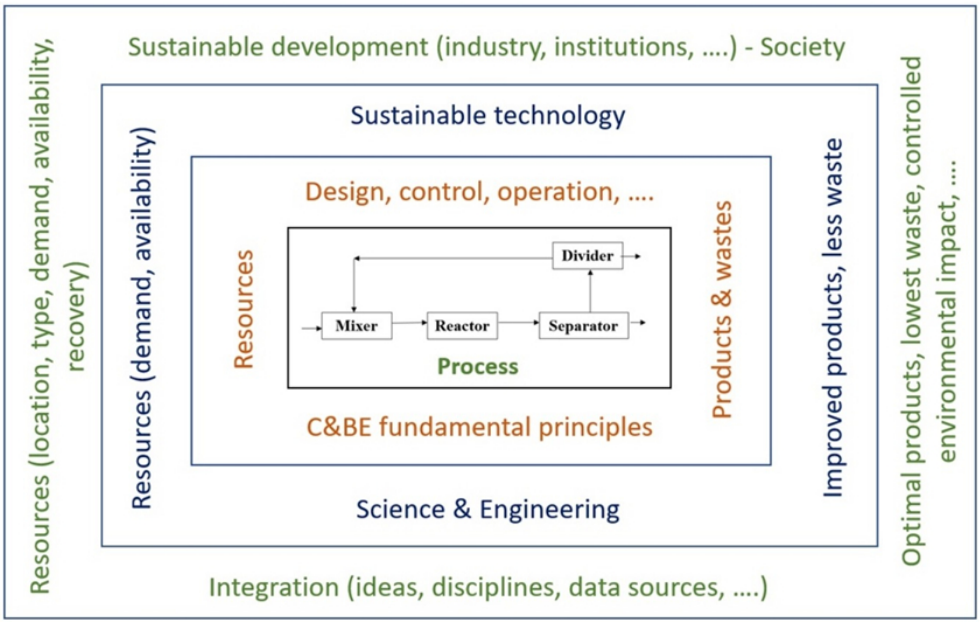

Fig. 2. The multi-layered view of chemical and biochemical engineering – adapted with permission from Gani et al. (2020). Copyright 2020 Institution of Chemical Engineers, Elsevier B.V.

4.1. BSc and MSc teaching

Based on another recent paper *Mastering digitized chemical engineering* by Feise and Schaer (2021), example contents of contemporary chemical and bio-chemical engineering courses are given in Table 1. This can be a good starting point for further discussion, updating and modifications.

In order to emphasize the existing dilemmas and differences in approaches, let us first briefly compare the Chemical Engineering curricula at Delft University of Technology and at the Warsaw University of Technology.

The BSc program in the Chemical Engineering Department at TU Delft is called *Molecular Science and Technology* and is schematically presented in Table 2. As one can see, the topics of the program are grouped in 5 categories: chemistry, mathematics, physics, engineering and practicals. In the first year all classes are common and obligatory. From the 2nd year on, next to the core topics specialisations begin and students

Table 1. Qualification framework and curricula for science-oriented chemical and bio-chemical engineering courses (based on data given by Feise and Schaer (2021))

Competences	Content	
	Bachelor level, 180–210 ETCS	Master level, 120-90 ETCS
Methods	– fundamentals – processes – systems – simulation – optimization	– complex problems – new scientific methods – incomplete data
Design	– design studies – design requirements	– new products – new processes – unusual design
Evaluation	– literature studies – experimental design	– data evaluation – information gathering – technology evaluation
Engineering skills	– project – application – safety, health – environment – economy – theory vs. practice – interdisciplinary – communication	– combining knowledge – manage complexity – self-learning – responsible care – solutions with profound methodic skills
Key capabilities	– time management – team – study skills – international collaboration – English – leadership – long-life learning	

can choose between materials, synthesis and engineering. An interesting part of the curriculum are the laboratory classes: Learn to Research, where students develop practical research skills. The first semester of the 3rd year is filled with a minor that gives students the opportunity to broaden their horizons and explore a subject that interests them, e.g. software design, business administration, modern drug discovery, economics, sustainability or law and management. They can also choose to take a cohesive combination of modules at a foreign university. A well-chosen minor can help to find an optimum career direction or to decide which Master's programme to take after completing the BSc programme.

In Warsaw University of Technology the Chemical Engineering course at the BSc level lasts 7 semesters (3 and half year) – there are no specializations, the teaching is carried out following the common program (core curriculum), also shown in Table 2. This fundamental program can be supplemented by students of Year 2 with a few chosen electives covering a wide spectrum of contemporary issues in science and technology, which can be useful for chemical engineer – Biomechanics of Flows, Scientific and Patent Information, Introduction to Enzymology, Natural Polymers, Safety of Chemical Reactors, Simple and Multiple Emulsions for new Technologies, Neural Networks, Introduction to Technical Biochemistry and

Table 2. The BSc programs at TU Deft and WUT. Note that at TU Delft some specific topics are taught within three specializations – Materials (*sM*), Synthesis (*sS*) and Engineering (*sE*)

BSc program		
Name of studies	Molecular Science and Technology at Technical University Delft	Chemical Engineering at Warsaw University of Technology
Group of subjects	**Year 1**	
Mathematics	– Calculus 1 & 2	– Mathematics 1 & 2
Physics	– Quantum Chemistry and Physics	– Physics 1 & 2
Chemistry	– General Chemistry – Organic Chemistry and Structural Analysis – Chemical Analysis Methods – Inorganic Chemistry	– General and Inorganic Chemistry
Engineering	– Chemical Thermodynamics – Introduction to Chemical Engineering	– Introduction to Chemical Engineering – Fundamentals of Engineering Calculations 1 & 2 – Electrotechnics and Electronics
Practicals	– Lab – Basic skills – Learning to Research 1	– Lab – General Chemistry – Fundamentals of Material Engineering – Informatics Technology – Engineering graphics
	Year 2	
Mathematics	– Statistical Methods – Linear Algebra and Differential Equations – sM & sE	– Mathematics 3
Physics	– Physical Chemistry and Kinetics	– Physics 3 – Physical Chemistry
Chemistry	– Material Structure and Properties – Biochemistry – Catalysis – Theoretical Chemistry – sM – Chemistry and Physics of Solids – sM – Organic chemistry 2 – sS – Theoretical Chemistry – sS – Physiological Chemistry – sS – Biomolecular Chemistry – sS	– Organic chemistry – Analytical chemistry
Engineering	– Transport Phenomena – sM & sE – Separation Technologies – sE – Chemical Biotechnology – sE	– Process Thermodynamics – Heat Transfer – Fundamentals of Fluid Mechanics – Quality Assurance Systems
Practicals	– Learning to Research 2	– Numerical methods – Lab – Physical chemistry – Lab – Organic Chemistry

Table 2 [cont.]

BSc program		
Name of studies	Molecular Science and Technology at Technical University Delft	Chemical Engineering at Warsaw University of Technology
Group of subjects	**Year 3**	
Engineering	– Numerical Methods – Statistical Thermodynamics/ Spectroscopy – sM & sS – Chemical Reaction Engineering – sE	– Process Kinetics – Transport Phenomena – Fundamentals of Processes and Process Equipment 1 & 2 – Fundamentals of Biotechnology – Fundamentals of Environmental Protection – Chemical Reaction Engineering 1 – Introduction to CFD – Process Automatics
Practicals	– Chemical Product Design	– Lab – Process Thermodynamics – Lab – Process Kinetics – Lab – Process Equipment
	Year 4 (7th semester)	
Engineering		– Chemical Reaction Engineering 2 – Separation Processes – Safety of Chemical Processes
Practicals		– Industrial Processes Design

Special Media in Chemical Engineering. However, in Year 3 there are electives, which are grouped in two specializing modules:

- *Informatics in Chemical Engineering* (topics: Introduction to CFD, Computers in Designing of Process Documentation, Modelling of Dispersed Systems, Modelling of Transport Phenomena with MatLab, Computers for Technical Drawings) and
- *Chemical Engineering in Advanced Technologies* (topics: Chemical Product Engineering, Microreactors, Separation Methods for Pure Technologies, Renewable and Alternative Energy Sources, Integrated Processes).

Additionally, the core program at the WUT is completed with a group of obligatory humanistic and social classes including Economy, Philosophy, Ethics and Foreign Languages.

The Master program in Chemical Engineering at TU Delft offers two alternative tracks:

- *Process Engineering* and
- *Chemical Product Engineering*.

Both tracks share several common obligatory courses including Applied Numerical Mathematics, Molecular Thermodynamics, Molecular Transport Phenomena, Product & Process Design, Ethics & Engineering, and a Design Project. Additionally, each of the two tracks has three track-specific obligatory modules: Design & Synthesis of Advanced Chemical Products, Quantum Properties & Structure of Materials, and Soft Matter for Chemical Products (track Chemical Product Engineering), and Process Dynamics & Control, Applied Transport Phenomena and Reactors & Kinetics (track Process Engineering). Finally, there are circa 25 elective courses that the MSc students of Chemical Engineering in Delft can choose from.

Coming back to the new teaching areas discussed in the previous section, one can see that the chemical engineering curriculum in Delft is strong in courses related to advanced materials. Process intensification, electrification, electrochemistry and energy storage are offered in elective courses, while elements of digitalization are not yet a part of the program.

It needs to be mentioned that TU Delft offers the students interested in biotechnology/bioengineering a separate BSc/MSc program called *Life Science & Technology*. That program is coordinated by the Department of Biotechnology and ends with three alternative specializations: *Biocatalysis, Biochemical Engineering* and *Cell Factory*.

The Master program at the WUT lasts 3 semesters (one and half years) and consists of four specializations:

- *Industrial Processes Engineering* (focus on physical and chemical phenomena taking place in industrial processes as well as on designing and modeling of reactors and processes),
- *Bioengineering* (focus on modelling, designing and performing processes carried out with contribution of microorganisms and/or biological substances),
- *Dispersed Systems Engineering* (focus on modelling and application of micro- and nano-dispersed for process and environmental protection as well as for chosen issues of influence on human body as pollutants or drug carriers), and
- *Nanostructural Products Engineering* (focus on modelling, designing and performing processes in industry and/or medicine).

In all specializations students are taught some common subjects such as: Fluid Mechanics, Mathematics, Computer Simulation, Process Dynamics, Process Optimization, CFD, Practical and Economical Aspects of Process Design, while in each specialization dedicated obligatory and elective classes are available.

4.2. Post-MSc teaching

In the Netherlands internationally unique post-Master designer programs have been developed and practiced for many years. Those two-year programs are offered within the framework of Stan Ackermans Institute by Dutch universities of technology aiming to put students on a faster track to a successful career in industry. All candidates that successfully finalize one of the programmes are awarded the degree of *Professional Doctorate in Engineering* (abbreviated PDEng). Consequently, the PDEng programs are certified by the Dutch Certification Committee for Technological Design Programs consisting of representatives from the Universities of Technology in The Netherlands, the Council of Central Industrial Organizations in The Netherlands and the Royal Dutch Society of Engineers. The courses offered within the above scheme include: Bioprocess Engineering, Chemical Product Design, Energy and Process Technology, Process & Equipment Design, and Process & Product Design. Each starts with a year of advanced education, followed by a major design project of eight to twelve months in a company. Because of a clear industrial orientation, the lecturers are often delivered by experts with a long industrial experience. In contrast to the BSc and MSc students, the accepted participants of the PDEng programs have a status of university employees and are remunerated, similarly to the doctoral candidates.

In Poland, *Implementation doctorate* is a new post-MSc program aiming at scientific career development. The main goal of the program is to create conditions for the development of cooperation between the scientific and socio-economic environments. Its main idea is the preparation of a doctoral dissertation that will help the functioning of a given enterprise. Implementation doctorates are therefore an alternative way of obtaining a doctoral degree, intended for people who – while developing their scientific careers – do not want to give up their professional work outside the university.

5. SUMMARY

Based on the literature and the observed industrial developments, we indicate the most important challenges in teaching chemical engineering and compare the respective curricula at two European universities. We restrict ourselves to two universities where we have personal, hands-on teaching experience.

In the paper we have presented some new challenges and megatrends within the chemical and related industries, that give rise to new teaching areas in chemical engineering curricula. Among those new teaching areas process intensification, digitalization and advanced materials will arguably play the most important roles in the coming decades. The three areas are interrelated with one another as digitalization and process intensification are destined to play the crucial role in, respectively, discovery, development and manufacturing of new materials, while new, advanced materials can be used for intensification of chemical processes.

The aim of this paper was just to focus the attention of university teachers and prospective decision makers on the most important challenges for contemporary teaching of chemical engineering.

We illustrated our discussion with the examples of chemical engineering taught at the BSc and MSc levels in two universities of technology, Delft and Warsaw, pointing out on how the above new teaching areas have been accommodated in the respective curricula. While not pretending to having resolved all the existing teaching dilemmas, we hope that the presented experiences will trigger further discussions on that topic within the chemical engineering community and will help arrive at curricula that will match the grand challenges of the century.

We did not formulate any hypothesis, as we are convinced that there is no single good and universal solution to the problem of how to follow contemporary trends in teaching. It is really impossible to say what method (way) is better – to follow the challenges is a complex process and in fact it is a trial and error method. Additionally, the suggested changes in curricula are rather indicative – i.e. they cannot be obligatory.

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