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The importance/role of education in chemical engineering

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Abstract
Chemical engineering as a skilled profession depends on the competencies of the individuals practicing it. Formal teaching of chemical engineering at universities only started in the 19th century. Informally, the subject has been in existence at least since Roman times. Highly skilled people have been recognised as a means to ensure prosperity and allow innovation for at least several centuries, as examples like the Bergakademie Freiberg show. It can be shown that skilled people flock to prosperous regions and prosperous regions develop where skilled people aggregate, modern examples include Silicon Valley and Northwestern Europe. The competences needed by a chemical engineer continue to broaden, e.g. sustainability, digitisation force changes in the education of engineers. The sheer volume of material cannot be covered in a tertiary study period and the speed of change makes knowledge obsolete very fast, which puts more focus on new life-long learning requirements. Modern, more individualised and context specific ways of education will develop, based sometimes on efficiency and cost of teaching and more often on effectiveness of learning.

Keywords
Education, life-long-learning, knowledge and skills, engineering, learning outcomes, active learning methodologies.
Introduction

Chemical Engineering is undoubtedly a skilled occupation and therefore depends heavily on the capabilities of the engineers practicing the profession. Formal education in chemical engineering is still a fairly young field, with the first courses only introduced in Manchester in the late 19th century. Nevertheless, chemical processes are much older and therefore have been taught to younger generations for at least as long as written history. Changes in what comprises chemical engineering education and how it is taught notwithstanding, the demand for this education will remain critically important for the foreseeable future if we are to develop sustainable solutions to the grand societal challenges facing mankind.

This paper briefly reviews the evolution of chemical engineering during the last century and a half, the need of industry for skilled staff and the effect on university education on the economy, lifelong learning and the role of education in innovation. The review shows that innovation has changed education since the ancient times and, conversely, innovation has been the result of education. The current era of digitalisation with its drastic changes in what is taught and how it is taught may signify the most significant transformation of education since the invention of the university in the 11th century.

1. The societal role of education: from the stone age to yesterday

Processes that facilitate learning have always been needed. Without education, a generation (or a society) is not adequately prepared for the demands of the world. Therefore, education has existed since the dawn of mankind, in some form or other. Perhaps not unexpectedly, whilst education has always developed to satisfy societal needs it can also have strong impacts on society.

For many people their time in school is arguably the most important part of their formal education. It is within the school setting, that most people learn to read, develop social skills and encounter authority other than that of their parents. As a consequence, many consider school and education to be synonymous.

Nevertheless, long before technology and schools, a word-of-mouth communication-based education existed. From hunter-gatherer communities to the invention of agriculture, beginning ten thousand years ago, people depended on word-of-mouth communication to acquire knowledge of the plants, animals and land upon which they depended.

Schools first operated in ancient Greece, at about the 4th century BC [Thomas G., 2021]. At that time education had become more diverse, reflecting more diverse societal needs, involving topics such as reading, geometry and rhetoric. From an early age, more emphasis was placed on physical education, presumably necessary for preparation for wars. Roman schooling broadly followed the Greek model.
There were small schools for privileged boys, which taught grammar. Then, the boys attended rhetoric schools, to prepare them for public life [Thomas, 2021].

Meanwhile, education developed in China, including the use of formal written exams for entry to some government roles [Pletcher, 2022]. With the fall of the Roman empire, western education survived in the monasteries of Ireland [Yerxa, 2006, Bardon, 2008, p.24] from whence Christianity returned to western Europe in the early Middle Ages [Duffy, 2012, pp. 22-23]. Some monasteries became centres of learning [Killeen, 2012, pp. 26-27]. Progress was made in relation to mathematics and medicine in the Arab world [Høyrup, 1987, Masic et al., 2017]. During the Middle Ages, guilds regulated apprenticeships for a variety of crafts [Stefon, 2022]. The protestant reformation, in particular the printing of the bible in languages such as German and English, led to increased literacy as people wanted to read the bible themselves [Arnove and Graff, 1987, p.4].

In later phases of history, the printing press became one of the most disruptive technologies to affect education in the 1500s, making literacy significant for far more people. Later, industrialisation generated the need for vocational, practical educational programs, so education also affected society by educating members to understand and develop technology [Thomas 2021]. Schools became instruments of capitalism, communism and other economic systems. All systems needed work forces possessing increasing levels of knowledge to develop economically, as will be discussed in later sections.

The substantial losses of male teachers during the world wars of the 20th century led to a dramatic rise in the number of female teachers. Societal democratization programs of the 20th century meant that education became more focused on participants with different disabilities.

The cold war (mid-20th century) generated the need for a more widespread education in natural sciences (physics, maths) and engineering. A broader appreciation of psychology also stimulated educational pedagogics to base itself on concepts from psychology, such as constructive learning [Biggs & Tang, 2011]. Aside from the transition to a progressive pedagogy, digital technology over recent years has also had an enormous impact on education. Representing another wave of disruptive technology since the printing press, digital technology, such as computers and the Internet, have dramatically changed how students learn and teachers teach. Education is more readily accessible now, and teachers have the tools to communicate more engagingly with wider audiences than ever before.

Thus, progressive education and digital technologies support novel learning methods, with increasingly autonomous students, relating more actively to and being more actively engaged in their own learning. They enabled the development of learning schemes with more individualised offerings and facilitated development of life-long learning programs. Demand for these will continue to grow, due to (among other things) increases in life expectancy and ever-shorter systems life cycles.
Thus, there is, and has always been a strong interplay between how education affects society and how societal changes affect education.

2. Industries need educated people

“lt takes a school to prosper” is a theme which has successfully repeated itself over the centuries. In 1765, Prinz Xavier of Saxony founded the “Kurfürstlich-Sächsische Bergakademie zu Freiberg” to reinvigorate the mining industry of Saxony after the loss of the Seven-years-war. The school is still alive and the Bergakademie has developed into a well-known technical university focusing on engineering for primary and secondary resources. The mechanics institutes provided education relevant to the needs of industry in Britain during the 19th century, particularly from 1851 onwards [Walker, 2012]. After the Second World War and particularly during the Cold War, governments greatly expanded vocational and third level education, in contrast to the pre-war period, where tertiary education was generally confined to a small elite (see [Valero, van Rennen 2019]). The same study showed that for 1,500 regions in 78 countries the regional economic growth correlated significantly with their university base. The study confirms a thesis of Mokyr [Mokyr 2022] that in many countries access to knowledge played an important role in their industrialisation.

Valero and van Rennen [Valero, van Rennen 2019] found that the effect of universities on regional economies is even stronger than the growth which can be attributed to human capital effects and innovation alone. Aghion et al. [Aghion et al. 2009] presented an extensive study showing that the effect of education is greater than simply the effect of universities. They provided evidence that primary and secondary education are the strongest growth promoters for any region which is not yet at the “technological frontier”. They rightfully caution that their study was limited to the states of the US and what constitutes “being at the technological frontier” will differ across the globe. Only regions which have already reached the “technological frontier” can benefit from the economic impact of tertiary education: the benefits are twofold: firstly, their own graduates remain in the region and contribute to GDP generation, and secondly graduates come from other regions further increasing economic gains. Silicon Valley in California is a good example of such a development. Within Europe, this kind of brain drain can be seen in action when considering the migration of university graduates from Greece, Spain, Portugal and Eastern Europe to Northern and Western Europe during or after their university education and remaining there. Figure 1 presents data from a selected group of European states regarding migration patterns, see [Brücker et al., 2013]. Over the period from 1980 to 2010 it shows the percentage of the citizens of each country who live abroad in one of the OECD20 states and compares it to the average of all European States. The data by Brücker
et al. [2013] also shows that the population with a higher (tertiary) education is roughly twice as likely to migrate compared to the rest of the population. It is worth noting that communities are generally wary of newcomers, nevertheless “knowledge migrants” tend to be viewed positively in receiving regions. Apparently, their economies and - in the case of chemical engineering - their industries have a need for these educated people.

![Figure 1: Percentage of citizens living abroad in one of the OECD20 states](image)

The importance of educated people for industry becomes apparent when the hiring practices of various sectors are considered. There is a large portion of the job market, in particular, but not limited to retail or event management, where prior education plays a minor role compared to social skills and on-the-job experience. Whereas in fields such as medicine and engineering employers have very high and very detailed expectations about the formal qualifications of their new hires. Consequently, there have been frequent and detailed debates regarding the appropriate content of (chemical) engineering degrees and - with the introduction of the Bologna Accord - the learning outcomes graduates must achieve. Various guidelines and recommendations [e.g. EFCE 2020], were finally formalised and nowadays are one basis of the accreditation process.

Notwithstanding a period of focus on ethics as part of the engineering degree after the so-called “Diesel emissions scandal” or “Dieselgate”, the current debate concerning the education of engineers revolves around “digitalisation” or “Industry 4.0”. The German Verband der Maschinen- und Anlagenbauer (VDMA) conducted an extensive study of the skills that will be needed in a future Industry 4.0 environment [Heidling et al 2019]. While the fundamentals (e.g. mechanics, material science, finite-element-simulation, multi-body dynamics) still remain fundamental, their usefulness
for Industry 4.0. projects was considered somewhere between 25% and 50% (fraction of survey respondents who considered these subjects as “very useful” or “indispensable”). Automation (77%) or Systems Engineering (60%) scored significantly higher as did special computer-based subjects (e.g. remote services or machine based learning). Discussions regarding non-core engineering skills, variously described as “social skills”, “transferable skills”, “personal skills” and “professional skills” have been ongoing for an even longer period. Figure 2 shows the results of a study of UK students and graduates (alumni) investigating the importance of various technical and non-technical skills for employment [Fletcher 2017]. Core chemical engineering ranked in the lower half of the list of importance. The top 5 positions were all taken by “transferable skills” (communicate effectively, work effectively as a team member, critical thinking, analyse information, gather information).

Figure 2: Average response for employment importance (alumni vs. full-time students); skills considerably exceeding the average difference between the full-time students and alumni groups are highlighted with an ‘X’. [Fletcher et al 2017]

3. The evolution or revolution of education from yesterday to today

3.1. The changing content

Chemical engineering education has evolved over the years, reflecting the changes in the technological and societal landscape of the relevant era. Indeed, challenges faced by the early generations of ‘chemical engineers’ in late 1800s, when George E. Davis delivered his first lectures on
the topic at the Manchester Technical School in 1888, were significantly different to those faced by the current generation of chemical engineers. The 20th century brought emphasis on the concept of unit operations, introduced in 1915, creating a new paradigm in chemical engineering and contributing to the definition of the structure of the discipline. After WWII, Chemical Engineering Science was defined as the understanding of the fundamental principles behind unit operations. With the more common use of automated control systems, process systems engineering was introduced in the early 60s, providing new approaches for synthesis and design of complex processes [Perkins, 2002; Stephanopoulos and Reklaitis, 2011]. This was followed by the acceptance of biochemical engineering as a field in the late 60s as industry developed products and processes involving fermentation and biomolecules.

In the European context, the report of the Working Party on Education (WPE) of the European Federation of Chemical Engineering [Gillett, 2001] highlighted the rapid changes in the industrial landscape and proposed areas that should be included in the core curriculum. It also commented on the depth to which they should be taught and the methods best suited for their delivery. This has since been updated to include new emerging priorities, first in 2010 [EFCE, 2010] and subsequently in 2020 [EFCE, 2020]. Similar reviews were undertaken in other areas of the world. For example, [Varma, 2008; Varma and Grossmann, 2014, Voronov et al., 2017] discuss in detail the history and evolution of chemical engineering courses in the USA including the move from traditional unit operations towards the emerging areas of biotechnology and nanotechnology. In particular, Varma and Grossmann (2014) declared ‘the current paradigm of our discipline is molecular engineering’. The authors also highlighted the rising importance of energy and sustainability as topics in the chemical engineering curriculum. This has been supported by a number of other reports over the years, e.g. [Allen et al., 2016; Haile and Glassey, 2012, Diwekar et al., 2021].

Around the world similar reports have reviewed chemical engineering curricula, in China [Yao et.al, 2022]), in Mexico [Hernandez and Villaseñor, 2015], in Africa [Case et al., 2016], just to mention a few. These reports highlighted the emergence of renewable energy sources and synthetic fuels, circular economy, sustainable engineering and new materials.

The increasing public awareness of the grand societal challenges and the UN Sustainability Development Goals (UNSDGs, n.d.) highlight the important role chemical engineers play in addressing climate change issues, supporting the transition to a low-carbon circular economy, contributing to the security and sustainability of energy, water and food supplies as well as developing solutions for the healthcare industry. In addition, the 21st century has brought an emphasis on Industry 4.0, artificial intelligence and machine learning tools in the process industries and the criticality of digitalisation skills [Feise and Schae, 2021] and led to the need for future
chemical engineers to develop intensified solutions for products and processes [Fernandez Rivas et al., 2020a, b].

These societal challenges increase the importance of interdisciplinarity, ethics and professional responsibility in engineering practice [Ocone, 2020] and emphasise the fact that technical expertise and engineering excellence must be underpinned by critical professional competencies and attitudes.

3.2. The changing education methodologies

With such significant changes in the content of chemical engineering curriculum and the rapid changes in society and technology, it is not surprising that educators are continuously pushed to develop innovative and engaging educational methods. Long gone are the days of an esteemed professor standing in front of a class of awed students, sharing their expertise in chemical engineering fundamentals that were difficult to acquire in other ways, given the scarcity of specialist textbooks. Students would take copious notes, hardly keeping up with the derivations of equations explaining the theory and practice of unit operations, let alone contemplating questioning the esteemed professor on the meaning of the concepts or discussing these with fellow students during lectures. Problem solving practice was gained in seminars and tutorials, usually led by research/teaching assistants, and often involved ‘cranking’ the handle and pushing numbers through the various equations copied during the lectures. Practical implications were explored in laboratory classes, often involving following ‘recipe’ instructions, noting down the results and analysing the observations in the context of the theoretical knowledge. This type of educational approach is still preferred in certain circumstances, particularly for students in the earlier stages of their studies, as Magana et al. [2018 and authors quoted within] evidence.

Arguably, there is nothing ‘wrong’ with this approach. However, the knowledge landscape has changed significantly, particularly over the last 30-50 years. The wealth of information easily accessible electronically through e-books and free journal article access, as well as various recordings explaining concepts with the help of diagrams and video clips that successive generations of learners have grown up with as a natural means of finding information, change the role of the traditional university educator. They are no longer the conduit of specialist information as much as a facilitator of ‘path-finding’ through the flood of internet-provided information, often of dubious accuracy. The learning interactions are becoming much more student centred, promoting active engagement of learners in all aspects of the process (Schaer & André, 2020). Whilst it is still essential that we convey the fundamentals of chemical engineering concepts and ensure in-depth understanding of these concepts in new contexts, we must do so in ways that engage the learner and utilise the rapidly evolving educational technology. A number of theoretical pedagogical frameworks argue that
engagement and active or interactive components increase the satisfaction of students and the effectiveness of their learning. One such framework is for example Keller’s ARCS (Attention, Relevance, Confidence, Satisfaction) model (Keller 2010, Low et al., 2022). It is thus not surprising that pedagogical research literature dealing with active learning methodologies increased rapidly over the last few decades (see e.g. a review of blended learning by Smith and Hill, 2019).

In chemical engineering education, for example, the number of articles on active learning methodologies increased notably since the publication of the Education for Chemical Engineers (ECE) special issue on this topic (ECE, 2018). Reported case studies on using a range of active methodologies in various aspects of chemical engineering education are too extensive to cover comprehensively in this article and thus only a selection of methodologies and applications are highlighted here. Examples of the demonstration of successful use of flipped classroom, peer instruction, gamification in teaching process control were presented by Rodriguez, et al., (2018), problem-based learning and gamestorming in plant and product design by Vega and Navarrette (2019) and Feijoo et al., (2018), respectively, student response systems (such as Socrates quizzes, used for formative assessments) in various aspects of theoretical concepts of chemical engineering by Romero et al., (2021).

Whilst the above highlighted some applications of active learning methodologies in technical aspects of chemical engineering education, section 3.1 discussed the shift in the emphasis on the ‘responsible’ aspects of the engineering education and the critical need to build appropriate attitudes towards sustainability and professional ethics as part of the professional competencies required of the engineers of the future. But how do you ‘teach’ someone such attitudes? The importance of sustainability education has been formally recognised in chemical engineering curricula for decades, yet the uncertainties in understanding, modelling, assessing, and managing for sustainability remain a ‘wicked problem’ (to paraphrase Diwekar et al., 2021). The technical aspects of sustainability assessment, such as Life Cycle Analysis (LCA) tools, have been taught for years. This was frequently achieved through lectures, case-studies or research-based teaching (Haile and Glassey, 2012, Jamieson et al., 2021, Mälkki and Alanne, 2017). Innovative approaches to teaching principles of recycling to future engineers, for example through serious games, are also emerging (Udeozor et al. 2022). However, attitudes and moral reasoning are much more difficult to build, even though experiences from process safety teaching indicate that this is possible (e.g. Butler et al, 2019, Stransky et al., 2021). Similarly, the importance of preparing students for the significant ethical challenges of their future professional careers has been recognised widely, with professional bodies increasing the prominence of this topic in accreditation requirements (e.g. IChemE, 2021 and Bolton...
et al, 2022). Supporting the development ethical consideration can be challenging, particularly from the point of view of chemical engineering educators, who may not feel best placed to support such discussions. However, the alternative of philosophy and ethics specialists delivering such topics to engineers is also fraught with challenges of relevance to engineering practice. Full integration of ethical considerations into the curriculum is, for example, argued by the Royal Academy of Engineering and Engineering Professors Council. They provide a valuable resource to enable such embedding into technical topics of the curriculum in the form of an Engineering Ethics Toolkit (EPC, n.d).

The global disruption in higher education due to the Covid-19 pandemic restrictions accelerated the transition to more technology enabled teaching and the use of blended learning approaches. Another recent special issue of ECE on digitalisation (Bodnar et al., 2021) features a range of articles not just on the need for and approaches to increasing the exposure of chemical engineers to digital technologies of the industry 4.0 (e.g. Feise and Schaer, 2021), but also on a range of technology enabled remote delivery teaching approaches (e.g. Bhute et al., 2021, Garcia Fracaro et al., 2021). Of particular interest are the developments in using gaming and immersive technologies for education and training of chemical engineers and operators [e.g. Nunes da Silva Júnior et al., 2021, Kumar et al., 2021, Solmaz et al. 2021, Low et al. 2022, Udeozor et al., 2021], given the wide-spread use of these approaches for entertainment of children and young adults. Although questions still remain about the level of likely adoption of virtual reality (VR)-based education for large classroom delivery, given the costs and the complexity of the technology involved, the progress in this area and the benefits gained by the immersive character of learning will undoubtedly ensure that such technology will play a part in effective delivery of chemical engineering knowledge and skills in the future [Garcia Fracaro et al., 2021].

An important question occupying the minds of educators throughout the pandemic was the delivery of important practical skills in the midst of global restrictions. A range of innovative approaches to this challenge have emerged (see a special issue collection of ECE journal, Glassey and Magalhães, 2020) from virtual laboratories (e.g. Liu et al. 2022) to ‘lab at home’ concepts (e.g. Santiago et al. 2022) and VR labs (e.g. Kumar et al. 2021). However, it is clear that exposure to physical equipment and the competent and safe handling of equipment underpin the level of confidence and competence of fresh graduates entering employment.

Indeed, discussions on the industrial relevance of chemical engineering higher education in and the employment-readiness of the graduates have also impacted on developments in educational
approaches. For example, Kavanagh (2021) in his editorial highlights the increasing difficulties of ensuring students experience professional practice through on-site tours and visits due to increasing student numbers, increasing security and health and safety restrictions, and the loss of nearby traditional chemical engineering industries. The articles featured in his editorial provide some valuable examples of how these issues can be at least partially off-set to improve students’ preparation for their professional practice. However, as the next section explores more deeply, there is a need for continuous up-skilling of a graduate through life-long learning in which universities, employers and, most importantly, professional engineers themselves, play an important role.

4. Life-long Learning in the Digital Transformation

Continuing education is the key to staying and remaining employable (as an individual) and competitive (as a company) in the increasingly globalised, digitalised world.

In addition to the many challenges that education policy and education providers are already facing today, continuing professional training needs to be developed into a key pillar of the educational landscape. To achieve this, Higher Education Institutions (HEI, i.e. institutions for tertiary education like universities and colleges), as the “think tanks of the future” [Kockmann et al. 2019], need a clear mandate for further education and appropriate and attractive business models [Wilk et al. 2020]. Furthermore, HEI must be enabled to react agilely to the permanent acceleration in the growth of information and knowledge and to constantly review and modernise their curricula.

4.1 What changes does the industry expect in terms of life-long learning

Today, the main focus of further education in many companies is on interdisciplinary skills. Teamwork, management of conflicts, communication, feedback and presentation skills, media competence, understanding of business administration and sometimes language skills are important elements of continuing professional training.

Some companies already understand that working in a cyber-physical world requires a high degree of autonomy and a need for autonomous teams and they have adjusted their curricula to address these changes. In general, it can be said that social skills are deemed important and will remain so in the future.

Companies attach great importance to the competence of employees for professional assessments in (and beyond) their field of expertise, and it is expected that the respective skills have already been taught in their academic training. This includes the ability to critically question facts, for example when dealing with the vast and omnipresent quantity of information provided on the internet, the quality of which very often cannot be relied upon. Ultimately, in addition to other cognitive
elements, self-management skills are required in particular, these are already partially supported by (internal) training courses.

How could this picture change in the coming years? According to a study by the World Economic Forum, a significant need for re-skilling and upskilling of professional knowledge is already postulated for 64% of all employees [WEF, 2018]. This is becoming a new, central challenge for education management in companies that are at best only partially prepared for it.

Extended lifelong learning has to compete for the time of employees who already find themselves in permanent overload mode today due to the compression of work demands and permanent oversupply of information in the “always-online society” [Heinrich Böll Stiftung, 2022].

Here – analogous to machine resources, for which downtime for maintenance and repair are a matter of course – a new balance must be found that allows for the necessity of further training. It is also expected that companies will develop new learning schemes with much more emphasis on individualised offerings rather than classroom formats for advanced specialist training as was suggested by a Delphi study as being the most likely scenario [Incore, 2014]. This could be achieved, for example, by means of (exclusive) educational partnerships between companies and HEI.

Educational effectiveness (in the sense of a defined, verifiable and sustainable acquisition of competencies) will be more important than educational efficiency (in the sense of a learning system geared towards speed and cost minimisation). Learning content that serves to refresh basic knowledge or is comparatively unspecific, on the other hand, will tend to be acquired in the classical “good but cheap” way [Incore, 2014], e.g. in the form of massive open online courses (MOOCs) or similar open learning platforms available on the internet. In general, it can be assumed that technical training measures throughout the entire duration of professional life will become considerably more important (frequency, duration, intensity) in order to provide employees with the necessary skills demanded at ever shorter intervals as a result of progress through new digital possibilities, e.g. in simulation applications. This is the best way to ensure employability in the long term.

The need for further training on the above-mentioned interdisciplinary topics will probably remain essentially unchanged, whereby it can be assumed that there will be a greater demand for competences for autonomous coping with complexity and thinking and acting in process networks (instead of process chains) and thus a more internalised self-management capability. The ability to actively listen and pursue verbal dialogue or discourse will remain important. The risk of losing good communication skills as a result of digitalisation must be counteracted [Kockmann et al, 2019].

4.2 How will professional profiles and careers develop?

We can only speculate as to the answer to this question. In general, it can be assumed that the engineering profession is less exposed to substantial changes than many other professions. After all,
engineering makes its own decisive contributions to the digitalisation of society and industry. As a creative, classically interdisciplinary function with a low level of routine and high problem-solving competence it will be difficult to replace it using digitalisation. However, the ever-shorter life cycles of methods and tools will increasingly force the need for retraining and knowledge enhancement in the future so as to survive in the highly dynamic context of digital transformation.

The professional profile of engineers will also continue to evolve, especially regarding inter- or transdisciplinarity. If, for example, one considers the tasks of the engineer along the asset life cycle (process design, engineering, construction, plant operation and dismantling), the close cooperation between process and automation engineers, established since the 3rd industrial revolution, is successively being extended to further disciplines. New specialties are being added, such as autonomous systems and artificial intelligence, and new, “hybrid” professional profiles such as data or bio-computer scientists are emerging. Coordination with specialist disciplines such as logistics, IT and data management will become increasingly important – along with the communication skills of the professional groups concerned.

Teams are thus becoming more dynamic, more diverse, and are expanding; it will therefore be increasingly important whether or not one speaks the “same language”. This has not always been the case in relation to the above-mentioned example of the process and automation engineer. In this respect, the universities must also make a contribution and promote understanding between disciplines, for example through inter- and transdisciplinary projects.

An interesting development can also be postulated for the professional profile of managers in the process industries. Since the seamless digital link in the value-added process means that classical management tasks, e.g. in interface management, are no longer necessary and that work processes are increasingly carried out by employees or teams with a high degree of autonomy with digital support, the leadership component will become increasingly important. Managers will have to act much more effectively as motivators, they will have to make the purpose of the company and their own unit understandable. This requires holistic thinking and acting more forcefully than today, so that the effects of corporate decisions on their own area, environment and society can be better assessed, and communicated. In addition, managers will have to take much greater care of the training needs of their employees (e.g. creating educational freedom, providing effective training opportunities) than they do today.

4.3 What additional academic life-long learning needs must be met?

If one considers the half-life of information and knowledge reproduction and the speed of digital change, especially compared to that of the 3rd industrial revolution, it can be postulated that the
engineer will not be able to successfully shape their professional life in the future without much more substantial technical training.

It can be assumed that the additional demand cannot be satisfied without continuing professional training courses offered by HEI and that there is also a need for new, more agile/flexible training formats.

The courses offered must cover both the refreshing of basic knowledge (e.g. mathematics or statistics for a better mastery of big data) and the deepening of new technologies, methods and tools. Industry would like to see training courses of high granularity, i.e. modules that can be easily combined with professional activity in terms of time/organization/logistics.

In this respect, the European approach to micro-credentials (European Union, 2021) could be an attractive standardised solution to build transparent and meaningful learning histories which would be beneficial for learners, employers and training institutions alike.

Finally, the need for “hybrid” professional profiles can be an interesting approach for individual professional development, since the greater interdisciplinarity or transdisciplinary demands in the world of work mentioned above would clearly benefit.

4.4 What learning models would be necessary for this?

In principle, learning models established today at universities or colleges with part-time study courses for professionals and distance learning offers are suitable. These HEI have established proven blended learning offers, in which traditional face-to-face events are sensibly linked with e-learning concepts. Here, online students are grouped together in small self-organized learning groups in order to link the social aspects of face-to-face communication with modern digital forms of learning. Presence (e.g. laboratory courses) and online phases are functionally coordinated in the learning process.

From today’s perspective, Covid-19 has triggered the accelerated development of digital and blended learning models throughout all HEI (see section 3.2), which will also be beneficial for creating lifelong learning offers for professionals in the long term.

In addition, intensive research and work is currently being carried out on immersive digital learning scenarios, for example in the EU project CHARMING (www.charming-etn.eu), in which immersive learning methods are being investigated and evaluated with regard to their suitability for further professional training.

In the sense of the highly granular educational offerings already mentioned, compressed offerings are also conceivable, in which the subject matter of a semester is condensed into a few days of in-depth education. However, such a model would have to be well thought out in terms of its interlinking of university and professional life and in terms of a scientifically sound education.
Of course, employers from industry and business administration as well as the employees themselves also have an important role to play. As already mentioned, on the one hand, new opportunities for learning must be created, and on the other hand, learning success will depend to a large extent on the personal willingness to continuously learn. The latter can presumably be increased if employers—in addition to providing such opportunities—allow a high degree of learning autonomy.

5. Education as a perspective and driver of innovation

Chemical engineering, based on the mathematical description of fundamental phenomena, has always been a source for innovation. The first paradigm developed by A.D. Little in 1915 [Hougen, 1977], introduced the concept of unit operations and their description by mass and heat balances associated by thermodynamics equilibria, has enabled large-scale production of commodities and contributed to industrial developments during the 19th century. The second paradigm, introduced by [Bird et al] in the 1960s ensured the development of quantitative models, based on the mathematical description of transport phenomena, and contributed to the optimisation of production facilities [Ramkrishna and Amundson, 2004, Kevrekidis, 1995]. The third paradigm [Charpentier et al. 2013] focuses on a multiscale approach to process innovation, based on mathematical description and modelling of phenomena occurring from the scale of the molecule to that of the process, and paves the way for the development of new products in integrated and intensified processes [Fernandez Rivas et al, 2020a,b].

The factory of future should be integrated, safe, energy and resource efficient, with the smallest possible carbon footprint. Innovation in new products and processes, as described by the Oslo manual [Oslo, 2018], will remain essential to meet the future society needs as well as sustainability demands.

The future of education is based on the mastery of fundamental knowledge and understanding of underpinning sciences, but also digital technologies, on engineering skills (ability to analyse, design investigate complex products and processes within a wide range of application fields, promoting interdisciplinarity) as well as professional skills (creativity, critical thinking, communication, ethics and entrepreneurship; EFCE, 2020), see Figure 3. It is clear that the acquisition of all these competencies, at an effective level, i.e; the ability to tackle complex problems and make decisions, will require fully educated engineers, supported by lifelong learning training courses. These competencies, acquired at a performance level, i.e. being able to efficiently reproduce the task carried out in a real professional context, can already be achieved through active teaching methodologies (see section 3.2). Some are already used and will continue to evolve as the educational experiences of learners and as future industrial and societal needs change. The concept of education 4.0 [Fisk, 2017] highlights nine trends (diverse time and places, personalised learning,
free choice, project based, field experience, data interpretation, change of exams, involvement of students and importance of mentoring) that should promote students’ engagement, active learning, acquisition of a wide array of competencies and help address the future needs of industry 4.0.

Figure 3: Skills expected from chemical engineering graduates (green=1st cycle, yellow=2nd cycle) [Feise, Schaer 2021]

Such highly educated future engineers will be able to contribute to continuous innovation of products and processes, thanks to their ability to understand, describe, model and optimise complex phenomena. The active teaching methodologies, promoting interdisciplinarity, reflective thinking and collaborative design have already proved to be efficient for breakthrough innovation, i.e. innovative products as well as innovative processes in a wide range of industrial sectors, not limited to the traditional oil and gas industry. Universities are also required to promote lifelong learning training for educators and teachers, in adapting and keeping up-to-date both their teaching methodologies and contents in the fast evolving learning context and technologies (Schaer & André, 2020).

Highly educated engineers are the key to meeting the challenges and transition of the futures. Strong connections between universities, industrialists and society remain necessary for innovation.

6. Conclusion
When considering chemical engineering education, one must keep in mind the typical lifecycle of an engineer. It starts with schools (primary and secondary) and continues with tertiary education (university). This is where the educational cycle starts to overlap with the beginnings of the professional cycle, involving mentors, leaders and professionals in the field who will continue to train the young people until they become mentors and/or leaders themselves and complete the life cycle with feedback on the secondary and tertiary studies. Today’s students are the inventors, innovators, and leaders of tomorrow. Educated and trained engineers are solving many of humanity’s problems, driving the global economy, and improving many aspects of our daily lives. Think about what you use and own in your life. People will continue to demand these products and services (and more!), yet the world’s resources and the capacity of the Earth to support this demand are dwindling at an alarming rate. Although arguably we all need to learn to curb our demands, given the continuous rise in global population, engineers must develop innovative solutions to these demands that are sustainable, safe and economically feasible. They design, improve and document the technological and service world around us. These days, several challenges make the direction and support of chemical engineering education more important than ever. Security, safety, resources and energy use, the circular economy, and a growing and ageing population are major challenges for new generations as they move into a more complex, interconnected, and interdependent world. A core priority is to ensure that we continue to have enough graduates to meet the growing demands of the workforce. Not surprisingly, a growing portion of this demand revolves around new, less resource-intensive and more efficient technologies. It is a key tool to be put at the service of the community to improve the human condition.

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract
Highlights:

- Societal role of education
- Education curriculum evolution
- Active teaching methodologies
- Life-long learning in the digital transformation
- Education as a perspective and driver of innovation