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Mastering digitized chemical engineering

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A R T I C L E I N F O

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A B S T R A C T

This paper highlights the importance of digitalization in chemical engineering industries, in the frame of Industry 4.0, and the consequences on the employability and profession of chemical engineers. Training content must necessarily evolve to meet industry expectations and maintain the level of innovation required to meet the challenges of the future such as competitiveness, global warming, or depletion of resources. Higher Education Institutions must evolve, and digitalization also makes it possible to provide new training methods and tools that will help the teachers to face these challenges.

1. Introduction

Digitization transforms the Chemical Industry rapidly across its entire value chain. Early examples of what is nowadays often called "Industry 4.0" were predictive maintenance and process automation. In 2017 Cefic recognized a rapid transformation of the entire horizontal value chain of the chemical industry due to digitalization, see (Winter, 2017). Today one experiences end-to-end supply chain integration and digitization of customer experience. Advanced analytics, often named "big data", sets out to change the way the engineering profession views the information it gathers and the interfaces a Chemical Engineer must manage.

Digitization, Digitalization, and Digital Transformation are often used almost interchangeably. While they are certainly similar in their dependence on computer power, they are distinguishable variations in the use of digital tools in the economic environment. "Digitization", as the most basic of the three concepts, simply refers to doing something in the digital space which has previously been done without computers. Examples are digital photography initiated in 1989 by Kodak's first digital camera, which replaces the paper photo by a digitally stored image or the transfer of a paper-based process from an analogue to a digital format. "Digitalization" requires a digitized format and adds (business) operations which are only available since the digital data is available. Examples might be the instantaneous access to e-mail via a smart watch introduced by Apple in 2016. True "Digital Transformation" changes the business behaviour and requires digitalization en route to a different product. Examples may be found in the information business where not only the form of delivery has changed, but also archiving and search are now part of the business offering of the information provider.

This paper is based on a presentation given at the joint Education Session of the 12th EUROPEAN CONGRESS OF CHEMICAL ENGINEERING and the 5th EUROPEAN CONGRESS OF APPLIED BIOTECHNOLOGY in Florence, Italy. It looks at examples of digitization and digitalization in the Chemical Industry, the thread of automation, what digitalization changes in the chemical engineering profession and how it impacts learning and education.

2. Digitalization in the Chemical Industry

Digitalization has impacted the Chemical Industry to varying extents. The ZEW-study (Gehrke and Rammer, 2018) recorded that in 2016 more than half of the chemical businesses in Germany had medium or high penetration of digital tools in production and logistics, see Fig. 1. Almost every company had some digitaliza-

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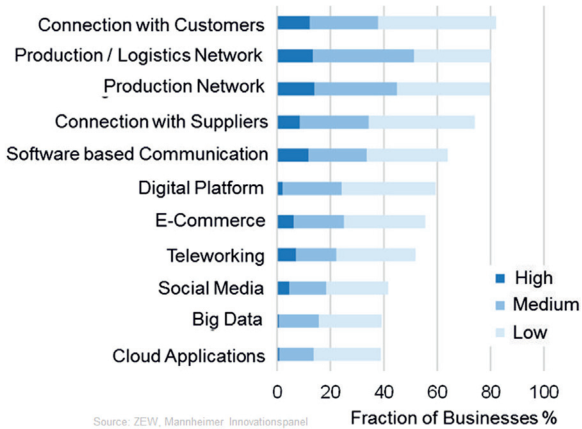

Fig. 1. Use of digital tools in the German Chemical Industry in 2016 (Gehrke and Rammer, 2018).

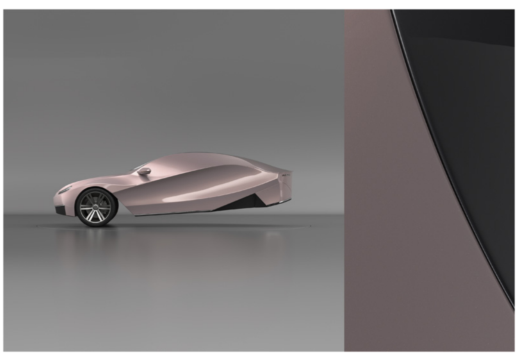

Fig. 2. Digital tool supports OEMs to visualize the effect of colors on large surfaces with different geometries (BASF, 2020); Picture: BASF.

tion in these fields as well as in the connection with its customers. Cloud applications and big data were lagging with more than 60 % of businesses having no applications in this field.

More recent studies in France (IESF, 2019) have also shown that 75 % of organizations have digital transformation projects underway, in which more than 50 % of engineers and scientists are involved. These transformations involve new offers to meet and anticipate market needs, new processes to improve operations and performance, corporate cultures and economic models.

Similar to consumer retail platforms, business-to-business platforms are changing the customer – supplier interaction in the chemical industry. Alibaba as one such platform shows 15,421 offers of acrylic acid from small lab samples to bulk shipments, with 26 Chinese offers together with suppliers from Iran, South Africa, Korea and Germany shown on the first page (Alibaba, 2019). Companies like Merck / Millipore Sigma (Merck, 2019) or BTC (BTC Europe, 2019) offer their product via a proprietary online catalogue.

A truly digitalized offering in the Chemical Industry is the AUROOM™ platform of BASF (BASF, 2020). The digital platform allows designers to access a database of photo-realistic virtual car colours. They can virtually paint these colours on their virtual car models and "gain realistic impressions of colours and effects on a complete car" (BASF, 2018), see Fig. 2.

In a collaboration with Bosch, xarvio™ Digital Farming Solutions developed its SCOUTING app, which identifies weeds from mobile phone pictures and provides treatment advice, into a smart spraying solution. The farm equipment manufacturer AMAZONE implemented this concept into its UX AmaSpot trailed sprayer, which can spot weeds in the field and apply herbicide only where weeds were detected (AMAZONE, 2019). The herbicide, its activity, application requirements and benefits have become a player in a data driven business offer.

3. The thread of automation

The smart spraying case provides an example which new opportunities arise from data driven applications and digital transformations. The changes these opportunities bring with them are the cause of significant changes in the job market and will change the portfolio of jobs available in the future. In a much-read study by Frey and Osborne (Frey and Osborne, 2017) they evaluated the susceptibility to computerization of all occupations described in O*NET – an online service developed for the US Department of Labor, which lists jobs and job titles and describes the occupation in a structured manner. Occupations are characterized in nine O*NET variables likely to be bottlenecks for computerization: perceptiveness, negotiation, persuasion, caring for others, originality, fine arts, finger dexterity, manual dexterity, and work in a cramped workspace. For each variable and the characteristics an occupation has for the respective variable, an estimate was developed whether "the tasks of this job be sufficiently specified, conditional on the availability of big data, to be performed by state of the art computer-controlled equipment" (Frey and Osborne, 2017). For each occupation the study derived a "Probability of Computerization". Fig. 3 shows the number and type of jobs in the US at the various levels of probability of computerization.

The largest fraction of jobs in high risk of computerization stems from sales, office and service areas. These are jobs which require interaction with the "business partner" (customer, applicant, user) but are fairly routine in their tasks. Every customer has seen and propagated such changes from clerks to computer in banking or hardware store check-outs. Engineering jobs rank mostly on the opposite end of the probability scale with the 33 % of employment least challenged by computerization. This is largely due to the high level of creativity engineering jobs require.

In 2015 the BBC together with Osborne and Frey had run a similar study in the United Kingdom under the title "Will a robot take your job?" (BBC News, 2015). Also here, production and process engineers ranked 329th, with rank 366 being the least likely to be replaced by a robot. Clearly, for engineers the robot will not take the job, but it will most certainly change the job. Keller (Keller, 2018) conducted 41 expert interviews and performed an online survey with more than 1000 participants to see how ten digital technologies will develop within the sphere of chemistry and chemical engineering. Fig. 4 shows the relevance of these digital technologies in 2018 (ordinate) versus the projected relevance in 2025 (abscissa). The number in and the size of the bubble show the relative change between 2018 and 2025. Clearly the study indicates that the most relevant technologies today will also be the most relevant in the medium future, with Modelling & Simulation, Big Data and Cloud computing leading and Blockchain and virtual reality at the lower end of the diagram. However, these technologies are also the ones gaining most in relevance. Overall digital technologies will double their relevance by 2025. This leads to a massive need to manage the competence of engineers in these areas, with regard to initial education just as much as continuous education (Keller, 2018).

4. Digitization in the chemical engineering profession

The move to digital tools and processes has a long history in chemical engineering. Forerunners have been engineering planning and design as well as maintenance. In 2005 Mosberger presented a piping model of a fluid bed catalyst cracker, when discussing "chemical plant design and construction" (Mosberger,

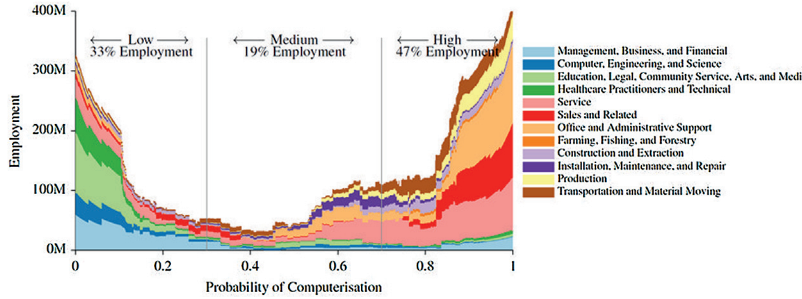

Fig. 3. Employment in the US affected by computerization (Frey and Osborne, 2017).

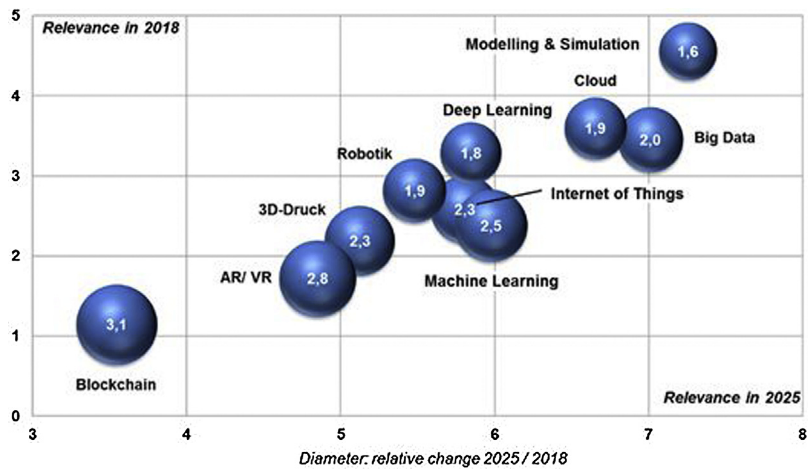

Fig. 4. Importance of 10 digital technologies in chemistry and chemical engineering (Keller, 2018).

2005), still made from Styrofoam and plastic tubing. Today the same is achieved with 3D-Caves where people can walk through a virtual 3D environment and inspect piping and positioning. Modern 3D scanning methods also allow the designer to integrate the existing environment and the new design into one virtual model. This has even become a feature of public interest (Sambale, 2017). Much older are CAE tools and scheduling software used for plant design and project management.

Digitalization concerns all the areas of innovation: energy optimization, economy of matter, reduction of releases, security of processes, recovery of by-products and waste heat, continuous research and development of new processes.

According to a SFPG study (SFGP, 2019) digitalization is involved in Process Design (for the acquisition of experimental data, the design of new processes using virtual reality or 3D printing), in Process Operations (for the digital transformation of a production site, the development of supervision platforms, the optimization and remote control of production), in the improvement of Processes Efficiencies (for recovery of by-products and energy) and in Process Intensification (for improvement of energy efficiency and product quality)

The VDI-Statusreport: "Bedeutung der digitalen Transformation für die chemische Industrie" discussed the adoption of Industry 4.0 in the German chemical industry (VDI, 2017). They found that next to Engineering (plant design, CAE) the most digitized area was logistics and supply chain, a finding which will be shared by consumers, see Fig. 5. In the area of maintenance, the internet of things and augmented reality are driving the digital transformation process with the intention of better plant availability and higher production flexibility.

Modelling and simulation have been a key feature of chemical engineering for more than a century. The new computing capabilities now allow to address problems of a size and complexity which was not conceivable ten years ago. In 2016 BASF formed a separate department focusing on Digitalization in R&D and installed its own supercomputer, with a computing power of 1.75 petaflops (1 petaflops equals one quadrillion floating point operations per second) which at the time of installation was ranked No 65 in supercomputers and remained the most powerful computer in the chemical industry worldwide at the time of writing this article (Top500, 2017).

5. Learning & education

5.1. Needs and expectations

How digitalization of the chemical industry and the chemical engineering profession will impact teaching and learning of chemical engineering or of engineering in general, has been the subject of several studies. In 2018 the 57. Tutzing Symposium (Tutzing-Symposium, 2018) developed five theses about the impact of digitalization on education:

1 Profound knowledge in fundamentals remains an indispensable pre-requisite even in times of Digitalization and must be taught appropriately
2 Digitalization requires frequent evaluation and appropriate re-structuring of curricula
3 Societies must qualify employees for the digital age and are obliged to develop a demand-oriented education system
4 Digitalization makes life-long learning even more important. Higher Education Institutions are challenged to develop education programs for industry and public services

Fig. 5. Adoption of "Industry 4.0" in Germany (VDI, 2017).

5 Digitalization requires better interaction and communication skills

These theses emphasize the continued importance of fundamentals for successful engineering careers ("*Students have to know how to make a mass or energy balance; they need to know how to design a reactor for safe operation, or how to determine chemical conversion and separation performance*." Kockmann, 2019) and at the same time stressing the need for frequent update of the education curriculum and systems which can adjust to a demand driven education (Tutzing-Symposium, 2018; Kockmann, 2018, 2019).

In North America, a recent study by Varma and Grossmann (2014), also highlighted the importance of a basic core of knowledge (mass and energy balances, thermodynamics, transport processes, reaction engineering, separations, laboratories and process design), while expanding to emerging areas such as materials processing, biotechnology, pharmaceuticals, food processing, particle technology, environment, energy and sustainability. Entrepreneurship, as a source of innovation, is also encouraged.

A recent NSF-funded study (Luo et al., 2015) on academic-industrial alignment also emphasizes the importance of the core-topic structure of chemical engineering including biochemical principles, their application to process safety, applied statistics, process dynamics, and applied process control through new teaching materials. The importance of soft skills, of practical experience and of active pedagogies, are also highlighted.

At the same time the World Chemical Engineering Council conducted a study of digitalization in chemical engineering education particularly in the Asia-Pacific region. They concluded that a future engineering curriculum should be a bachelor degree program covering today's chemical engineering content complemented by a graduate course on digital subjects like: mathematical modelling, programming tools and software, digital twins, algorithms and data structures, control systems and advanced sensors, data analytics and predictive maintenance, cyber security, digital business models.

Beyond chemical engineering, Heidling et al. (2019) looked at the impact of Industry 4.0 on Mechanical and Electrical engineering in the German industry. From 71 expert interviews and 224 company surveys they confirmed that fundamentals are still considered core of the engineering profession. However, the required competencies beyond the core show a strong impact of the global economic development over the last decades, see Fig. 6. The highest importance is assigned to competencies needed to work in a system with flat hierarchies (self-reliance, teamwork) followed by typical requirements for a globally operating industry (openness, learning aptitude, internationality). Agile methods and design thinking, as typical representatives of digitalization are still in the lower third of the list, surrounded by project management and leadership skills.

Since Fig. 6 represents an assessment of content required from universities and other higher education institutions' graduates, one can detect a certain time lag before a new requirement becomes accepted in the education community. On one hand this is a necessary precaution since many massively pushed requirements turn out to be a quickly forgotten hype in the long run. On the other hand, it is also a threat to the universities, since unmet educational needs will be covered by other providers (private Higher Education Institutions, or HEI, training companies, Massive Open Online Courses, or MOOC, providers). Kockmann (2019) shows some examples of how universities react to these developments. Examples reach from changes in teaching methods, through new teaching modules to "Digital Engineering"-degrees. In Germany the first four institutions (U Potsdam, HS Aalen, OVGU Magdeburg, U Weimar) offered such degrees in 2019.

The study by Heidling et al. (2019) determined that the need for knowledge outside the engineering core is still considered rather small by industry. Data / IT-Security as the highest-ranking digital knowledge is considered "very useful" or "indispensable" by only 58 % of the industrial representatives. Clearly classical skills like analytical thinking (92 %) or creativity (83 %) still outweigh the digital skills.

At the same time as the competencies required from an engineer by the job market change, the expectations of the learners change as well. Today's cohort of students is mainly composed from digital natives, who expect the use of digital tools and media from the education institution (Wilk et al., 2020). While digital natives have no entrance barrier against digital tools, they do not necessarily have digital competence. However, they very much have "digital expectations", namely: instant access, short, on my smartphone, only when I want it, for free, and virtually comprehensive like a search result from Google.

As Levine (2018) describes not only are the expectations of the students changing but also the needs of learning. The initial education received in school and at university or during vocational training has never been enough to last a lifetime for any profession. However, the speed at which learned knowledge must be replaced and the related competencies relearned has increased from decade to decade. Consequently, new ways of learning and teaching must be developed. The "Just in Time" Learner (Levine, 2018) is a consequence of this development, where people might find the need to re-orientate their work occupation. This is not limited to academically trained professionals but even more to occupations like truck driving, where automatically guided vehicles may wipe out

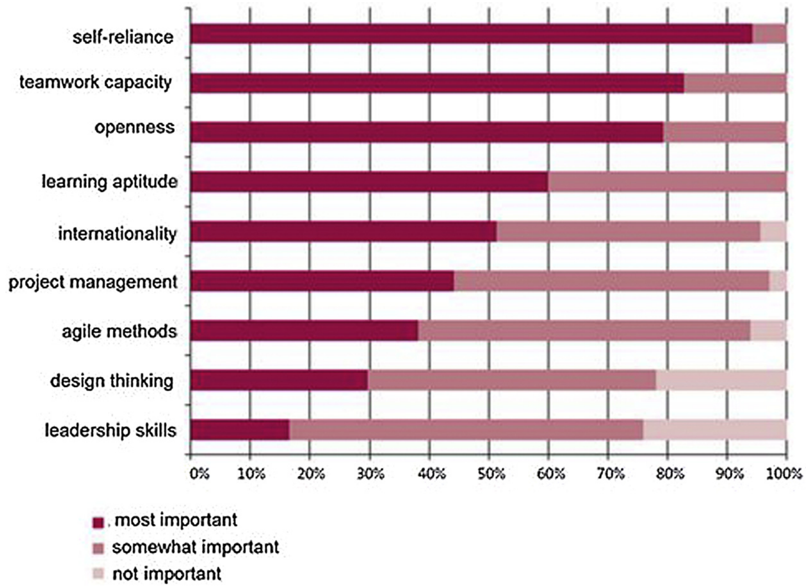

Fig. 6. Non-core competencies required from an engineer (Heidling et al., 2019).

an entire profession over the next 20 years. Consequently, Levine (2018) expects a demand for just-in-time learning much larger than the traditional higher education, today.

5.2. Digitalization changes how we teach

The first reaction in the education sector to the digital age were the use of digital tools to teach. While in Germany the 1980's was still the age of CAE (copier aided education), today's teachers rely on PowerPoint slides provided to the student via cloud storage. While this has shifted the cost burden from the student to the university computing department, it has not changed the way of teaching, which still relies heavily on lectures.

Similarly, the first generation of MOOCs has provided the same lecture, often at very prestigious institutions, as a video thus removing the need to be in the same room as the teacher when attending classes. Removing the need to move synchronously with the teacher in time and space has been the value proposition of MOOCs until today, which is intended to make education more "democratic" and accessible to people with less financial backing. However, even at the time of the highest number of tertiary students in the world ever, beneficiaries were not MOOC-providers or long-distance-learning agencies but mainly classical on-site teaching institutions (Cisel and Bruillard, 2012).

The student cohorts entering university now are digital natives (also called Generation Y or Generation Z).[1] Their learning behaviour is characterized by their ease with digital communication tools, their connectivity, their access to information, and their relationship to the authority (including teachers). They are used to doing several things at once, which during a course can be a strength and a curse, and experienced with free video tutorials. The next generation will even bring previous experience with online learning platforms during their high school education.

With such learners, traditional teacher-centred training methods, such as transmissive (where learning is done by transfer from the teacher, who possesses the knowledge, to the student, who must assimilate this knowledge) or behaviourist (where learning is a lasting modification of behaviour resulting from the consequence of particular training) pedagogies (see Joyce et al., 2014 for example), might not be the most efficient ones. Information is now available everywhere, at any moment, and the role of the teacher is to guide the learner in the construction of her or his learning, through interactions (with teachers and peers), completing both knowledge and skills. We talk about active learning (Louvain Learning Lab, 2020) or learner-centred pedagogy (Meirieu, 2006).

Active pedagogies, such as constructivism (where knowledge is actively developed by the learners, Piaget, 1964), socioconstructivism (which adds the importance of the social dimension, Berger and Luckmann, 1966) and finally connectivism (where learning and knowledge is brought by connections, made possible by digitalization, Siemens, 2005), are based on the interactions with teachers and peers, and on active learning situations, in professional context. Classical tutorials or practical work might remain interesting in these conditions, in providing active learning situations, but lectures might need to be adapted. New teaching methods, the most commonly known and applied being flipped classrooms (which reverses the nature of face-to-face and non-face-to-face learning activities), problem based learning (where the teachers' role is to support and guide reflection while encouraging learner autonomy and initiative), or project based learning (based on a socio-constructivist approach that allows learners to identify and formulate their own problems in order to develop skills) are developed (e.g. Schaer and André, 2020; Lorraine, 2020).

These active teaching methods can be associated with different tools, also brought by digitalization and allowing more interactivity, such as:

- learning analytics, "which involve the measurement, collection, analysis and reporting of data about learners and their contexts, for purposes of understanding and optimizing learning" (Ferguson et al., 2016). Most of these tools are digital, allowing instantaneous feedback, and most commonly used are Kahoot (https://kahoot.com/), Socrative (https://socrative.com/) or Beekast (https://www.beekast.com/fr/)
- video capsules, generally short and dynamic, that can complete some parts of the course or and illustrate resolution of the exercises. A lot can be seen on Youtube, or here for example

[1] Generation Y – Why -, which concerns the people born between 1980 and 2000, and the subsequent Generation Z – Zapping -, which corresponds to those born after 2000.

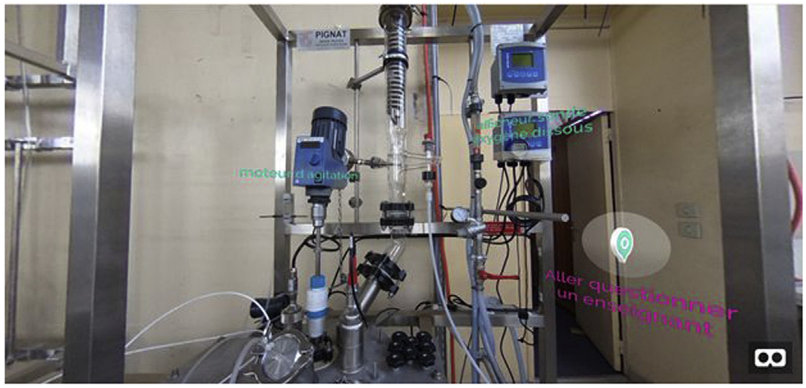

Fig. 7. Virtual lab for the Study of Mixing (Debacq et al., 2019).

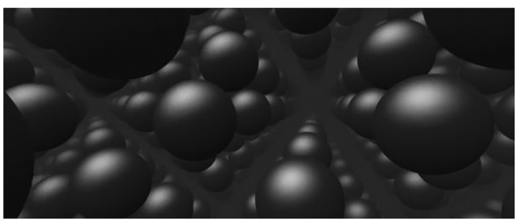

Fig. 8. Atomic arrangement in Solids, (MelChemistry, 2019).

of Heterogeneous Chemical Reactions : (https://www.youtube.com/playlist?list=PLN1pwVzM7WPiFLnC5dDt7ItdghVp-Eun2),
- mind maps, to illustrate the concepts related to a central idea and help students in organizing their knowledge. Mind maps are not necessarily digital, but software allows multiple online contributions, ensuring students active contributions. Commonly used are Coggle (https://coggle.it/), LucidChart (https://www.lucidchart.com/) or Framindmap (https://framindmap.org/);
- serious gaming, based on the association of game-based elements and teaching utility functions (broadcast a message, provide training…) in a context which departs from the only entertainment (Alvarez and Djaouti, 2014) can help varying learning situations. Again, not all games are digital, but digital offers many possibilities.

Complementing these tools, use of virtual reality, augmented reality, or subjective reality situations can also ensure and complete active learning activities.

Such examples of virtual labs for the study of mixing in practical works at different scales (see Fig. 7, Debacq et al., 2019) or the description of atomic arrangements in solids (see Fig. 8, MelChemistry, 2019) are already available.

Virtual reality has been used by universities to improve student engagement since computers have become available to every student. In 1996 Bell and Fogler (Bell and Fogler, 1996) presented VICHER an educational module for chemical reaction engineering based on virtual reality. The module already had graphically designed welcome centers, billboards with tasks and screens providing information similar to what might be expected in a chemical installation. Various rooms illustrated data required to solve the individual tasks available to the student.

A different type of game is represented by the PSC Process Simulation Cup (Chemstations Europe, 2020; Schöneberger, Fricke, 2017) where students are given a challenge to solve using process simulation software provided via a web accessible host. Monthly prizes and scoreboards try to establish a competitive spirit and increase student involvement. More than 20.000 submissions from more than 100 countries prove the value of this approach and make the PSC Process Simulation Cup (one of) the most global learning exercises in Chemical Engineering. The organizers also stress that the effort of preparing a challenge is significant, while the cost of multiplying it is marginal (Schöneberger, Fricke, 2017), which makes this online competition a typical MOOC.[2]

Digitalization of teaching has not replaced face-to-face teaching. In the experience of the authors almost every course in almost every university has moved to blended learning and integrated digital tools and concepts into their teaching. This may be as simple as chat times for student teacher interaction or go as far as online-training and homework platforms. Successful use of blended learning utilizes social interaction between teacher and student as a major success factor. Not all students can self-teach, irrespective of the self-teaching tool used.

5.3. Digitalization changes what we teach

The Bologna process introduced a common teaching model (three cycle, Bachelor – Master – PhD), module descriptions and ECTS credits for academic education in Europe. ECTS credits measure how much of an academic year is taken up by a specific module. Number, size and content of the modules are the responsibility of the program designer, however. For chemical engineering several qualification frameworks were developed, e.g. in Germany (ProcessNet, 2018), Europewide (EFCE, 2010), which try to define the requirements for first (Bachelor) and second (Master) cycles in chemical engineering or generally for any engineering education (ENAEE, 2018). The frameworks provide outcome descriptions and refrain from prescribing curricula.

The EFCE Bologna Recommendations for Chemical Engineering Courses (EFCE, 2010) describe the required competencies of a chemical engineering graduate in six areas of competencies (learning outcomes):

- Knowledge and Understanding;
- Engineering Analysis;
- Engineering Design;
- Investigations;
- Engineering Practice;
- Transferable Skills.

The recommendations of the European Accredited Engineer (ENAEE, 2018), which address specifically the education of engineers in the European Higher Education Area describes both Bachelor and Master Degree programmes with references to eight areas of competencies : the first five are the same as those described

[2] MOOC = Massive Open Online Course.

in the 2010 EFCE document above, and the Transferable Skills part is detailed in three points:

- Making Judgment (that include social, ethical, technical and financial aspects);
- Communication and team-work (in national and international context with their peers and with society in general);
- Lifelong Learning (to follow development in science and technology and continuously improve their knowledge and skills).

The future version of the EFCE Bologna Recommendations (EFCE, 2020) will include and detail these three points.

Both recommendations stress that chemical engineering labs should keep a consequent dimension in chemical engineering programmes.

Higher education institutions should therefore regularly evolve, not only in teaching methodologies, but also in terms of teaching content, to meet the changes in the materials and energy transformation industries and to meet employers' expectations.

- Numerical methods are becoming increasingly important, whether for the description, simulation, optimization, or extrapolation of complex, strongly coupled phenomena. Future engineers will need to be comfortable with commercial codes, but also able to develop new ones.
- Artificial intelligence tools now make it possible to adapt and optimize production systems in real time. Future engineers should also be comfortable with these tools, in addition to those related to process dynamics and process control.
- In a constantly changing world, with the regular release of new tools and new products, future engineers will have to quickly train and adapt themselves to new methods and constraints. They must learn to train throughout life.
- With the expansion of the fields covered by the discipline, future engineers will also have to be able to extend the methods and tools of chemical engineering to new and various fields.
- Finally, the importance of communication, critical analysis, teamwork, and problem solving has already been emphasized. These concepts are difficult to learn passively and getting professional experience during training seems necessary.

Higher Education Institutions face numerous injunctions (in addition to those related to the evolution of learners, detailed in previous paragraph): new subjects are to be taught, the field of application of the discipline is widening, while the time for teaching remains constrained.

Fig. 9 shows the German Qualification Framework for science-oriented chemical and bio-chemical engineering courses. The Bachelor modules (green, 180 ECTS credits) are arranged in five main competencies: Methods, Design, Evaluation, Engineering Skills, Key Capabilities.

Mathematical and science fundamentals are part of the "Methods" capability together with simulation and optimization algorithms. General science capabilities like experimental design or literature studies are covered as Evaluation. Typical engineering occupations like design methods, health and safety or project management complement the general scientific subjects. Soft skills, personal skills or transferable skills make up the fifth competency "Key capabilities", where e.g. time management, international cooperation and teamwork are collected.

The additional 120 ECTS credits in the Master course (yellow) are divided between the four technical / scientific competencies, while the "key capabilities" are supposed to be practiced and improved, but not expanded during the second cycle.

An engineering graduate will develop the capabilities or competencies shown in Fig. 9 to varying degrees. The ProcessNet

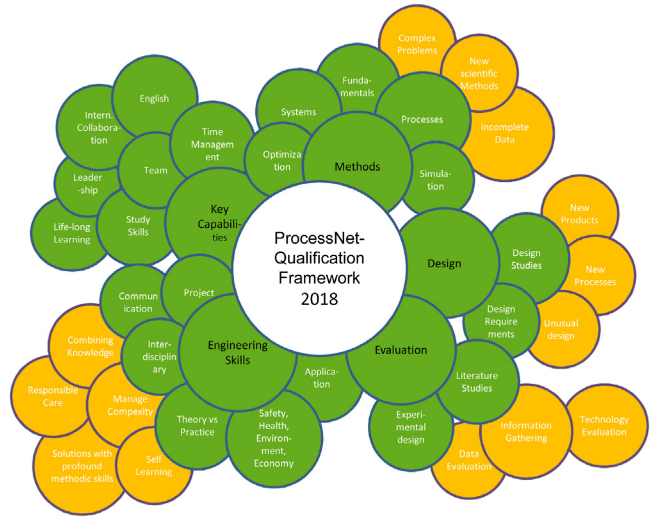

Fig. 9. Qualification Framework and Curricula for science-oriented chemical and bio-chemical engineering courses (Feise et al., 2016).

– Qualification framework (ProcessNet, 2018) uses Bloom's Taxonomy (Bloom et al., 1956) to describe the various levels from knowledge (low) to evaluation (top). Apart from additional subjects the master's degree must provide higher levels of competence in the fields covered by the bachelor's degree. Fig. 10 shows the six levels of competence in a triangular diagram against the dimensions of Completeness and "Speed of Study" (effort). Clearly, not all three dimensions can be maximized within a study program, e.g. very short study times (high speed of study) can only be achieved if level of completeness and level of competence are kept sufficiently low. Any study program must therefore be a compromise between the three dimensions of competence, completeness and speed. The qualification framework therefore tries to assign necessary levels of competence and completeness for the three cycles (bachelor, masters, PhD – not discussed here), where the bachelor degree scores higher in the "speed" dimension, which describes effort of learning and resource requirements, than the master degree, but lower in levels of competence and completeness achieved.

Engineering programmes - chemical engineering being no exception - are considered very demanding programs by students and teachers. In such a program, adding subjects to the five capabilities will not be possible without compensation. Until the 1990's the typical compensation for increasing amounts of science to be taught was lowering the level of competence achieved. Many engineering courses dropped lab classes or internships for more lectures where subjects can be presented but no competences beyond "Comprehension" (level 2) can be achieved. With the introduction of the Bologna Process and the development of qualification frameworks the view changed, and program designers started to make choices. This accelerated the already existing trend towards more specialized engineering degrees, where e.g. one university in Germany offers a degree in chemical-and-biochemical engineering next to a degree in chemical process engineering.

The needs described above (Chapter 5.1 Needs and Expectations) require additional material to be introduced in the general engineering curriculum. For some students, even a very specialized course focusing on the digital transformation of industry and the required engineering knowledge might become attractive. Currently, the Engineering competencies needed for digitized Chemical Engineering are necessarily unknown, because the field still changes very fast. Clearly, digitalization will not be done by engineers alone, so at least engineers will need to learn the vocabulary, the probabilities and limitations of statistics, data models and

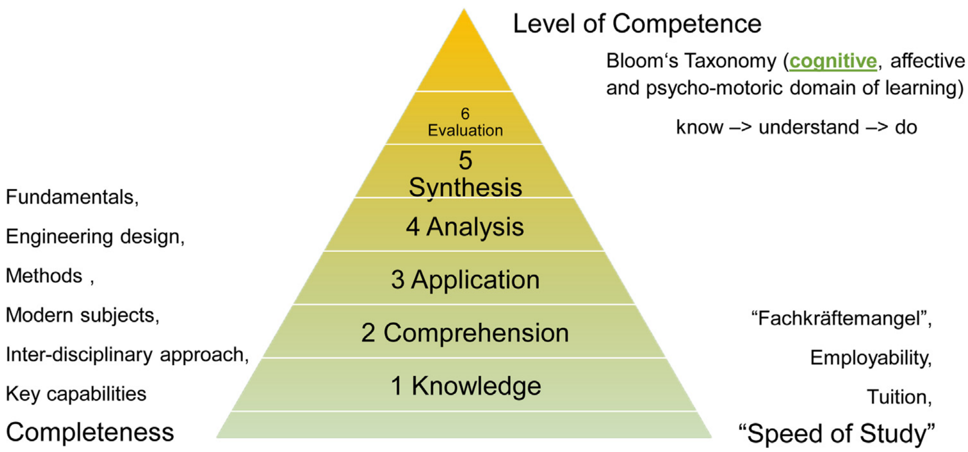

Fig. 10. Bloom's Taxonomy on Levels of Competence versus Completeness and Effort (Feise et al., 2016).

data combination to be able to interact with their respective expert colleagues. Over the next decade data analytics tools will become widespread engineering tools like CAD, FEM or flow sheet modelling, which many engineers perform. It remains unclear whether they will become general tools like word processing or spreadsheet calculations, however.

Since additional material will need to be accommodated in all cycles of the degree, it will be the task of the university staff to decide which pieces to shorten, which content to remove in order to make room for the new material. At the same time, electronic teaching means can improve the level of competence achieved by the students. They should not, however, be used to increase the amount of material presented to the students. In the end retention matters, which will not improve if more information is presented over a shorter period of time. Future employers do not benefit from what has been taught, but from what has been learned and what the graduate can do when he or she leaves university. Being able to learn, while necessary, is not sufficient.

6. Conclusion

Digitalization has brought and continues to bring important changes in Chemical Engineering industries and activities. It logically impacts the contents and modes of training, which need to cover wider areas of knowledge and propose active learning pedagogies focusing on the development and implementation of skills.

Digitalization is both a source of change and a potential for development, but these evolutions should also be accompanied by adequate training for teachers, both in new teaching methods and in emerging areas of application. However, digital methods, whether used for teaching or for process simulation, only allow (for the moment) to reproduce what they were developed for. The human added-value, for other forms of explanations, other ways of thinking and for innovation, remains essential in education in engineering.

Declaration of Competing Interest

The authors report no declarations of interest.

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