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Process intensification education contributes to sustainable development goals. Part 2

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ABSTRACT

Achieving the United Nations sustainable development goals requires industry and society to develop tools and processes that work at all scales, enabling goods delivery, services, and technology to large conglomerates and remote regions. Process Intensification (PI) is a technological advance that promises to deliver means to reach these goals, but higher education has yet to totally embrace the program. Here, we present practical examples on how to better teach the principles of PI in the context of the Bloom's taxonomy and summarise the current industrial use and the future demands for PI, as a continuation of the topics discussed in Part 1. In the appendices, we provide details on the existing PI courses around the world, as well as teaching activities that are showcased during these courses to aid students' lifelong

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learning. The increasing number of successful commercial cases of PI highlight the importance of PI education for both students in academia and industrial staff.

1. Introduction

The current world economic order demands professionals to be creative and innovative, no matter their field of work. This is particularly important in chemical and process engineering disciplines that significantly contribute to addressing the grand challenges faced by society on climate change, energy transition, and freshwater management as stated in the UN-SDG (Sustainable Development Goals, 2019; Ausfelder and Hanna Ewa, 2018; Boulay et al., 2018; CEFIC and DECHEMA, 2017; Stork et al., 2018; Klemeš and Jiří Jaromír, 2020), and also the ones related to the technological need of creating circularity of organic, carbon and inorganic resources. This is also connected with water source management, including its quality and footprint to warrant an overall sustainable process/product paradigm, whereby life cycles assessment plays a key role (Boulay et al., 2018). Together with these challenges, the chemical industry constantly seeks to increase energy savings, an objective of the chemical industry since the 70 s while reducing their greenhouse gas emissions.

Process Intensification (PI) is a relatively new toolset for addressing these goals that is gaining momentum in industry and academic circles. We provide an updated definition of what PI in the context of education for chemical engineers in Part 1 (Rivas et al., 2020), and is summarised as 1) an approach “by function”, a departure from the conventional process design by unit operations, and 2) an approach that focuses not only on the process itself, but also on what happens “outside or as a consequence of the process”.

The recent International Conference on Process Intensification (IPIC2, Leuven 2019 (EFCE, 2018)) included an academic segment, an industrial segment, as well as several workshops on selected topics: continuous manufacturing, multifunctional processes, alternative energy sources, and 3D printing. During the Lorentz Centre Workshop held in June 2019, introduced in Part 1 (Rivas et al., 2020), the relevance of PI for the education of the professionals of tomorrow was discussed. This paper expands on the tools available to meet this scope.

Traditional chemical engineering courses are based on unit-operation oriented topics, such as chemical reaction engineering, mass and heat transfer, polymer processing, particle technology, etc (Stankiewicz and Yan, 2019). PI education requires students to master those fundamental concepts as well as material-specific functions (e.g. surface area, permeability, responsiveness to induction heating and microwave heating, and catalysis) to solve complex chemical conversion and/or separation processes. Introducing these concepts in the study of processes and application of the PI principles will require consequential changes in the current teaching methods and content. For this reason, we must update the 20-year old toolbox approach to PI and include material design and engineering, i.e. concepts and representative examples on how to conceive and integrate materials into existing and new designs to contribute to the industrial and ecological challenges of today.

This article details current provisions and proposals of how to introduce PI into chemical engineering education and training. It also specifies concrete resources and materials appropriate for academic settings (BSc, MSc, and PhD) and professionals working in the industry to effectively create long-term learning of the PI principles.

2. Current educational programs on process intensification

The number of educational programs in chemical science and engineering programs offering PI courses has grown in the last decade, as evidenced by a database of the PI courses offered at several universities and institutes we have compiled. Each of these courses has empirical experience on advantages and challenges associated with the type of delivery they chose. The journal *Education for Chemical Engineers* has agreed to update this information (Supplementary material – Appendix 1) regularly to include changes and additions to the database. Furthermore, we have included some of the books used. While this number of chemical engineering programs active in PI is significant, one could stop to wonder: if this is enough?

Discussions during an expert panel workshop on PI education (Rivas et al., 2020) recognized that the introduction of new courses in existing curricula is one option to teach PI at a tertiary level. However, this may be difficult in the already full curricula that are often structured to fulfil professional accreditation requirements (e.g. IChemE, 2019 (Institution of Chemical Engineers (IChemE), 2019; ABET, 2017). A more realistic approach is to introduce PI elements (if not the whole framework) across several courses. For this strategy to succeed, students must have basic engineering knowledge first (Part 1, Figure **3**). For this reason, these theoretical courses can be leveraged to introduce students to PI and sustainability concepts in combination with project-based education, in which students use the lecturer-student contact time to practice solving problems.

The precepts of Bloom’s Taxonomy, which describe and order the different cognitive skills, offer a structured way of teaching PI. If PI is a departure from the conventional process design by unit operation, with a focus not only on the process itself, but also on environmental and sustainability issues, then what are the conditions that we should put into place for the students to master very high-level competencies (Rivas et al., 2020)? When “complex problems require sophisticated problem-solving skills and innovative, complicated solutions” (Madden et al., 2013), educators must be creative designers of learning experiences that move away from traditional learning (Henriksen et al., 2019).

Bloom’s Taxonomy (Bloom, 1956) has long been recognised by the international community of pedagogical experts as an effective framework that is applicable across different educational disciplines for conceiving and guiding learning outcomes. Revised in 2001, it conceptualizes and classifies cognitive processes that the brain performs and orders those hierarchically from the most introductory and accessible (remember) to the most advanced and integrative (create). The three cognitive processes at the bottom of the Fig. 1 **(right triangle)**, *remember*, *understand* and *apply* are the “lower order cognitive skills” or LOCS, while *analyse, evaluate and create* are “higher order cognitive skills” or HOCS (Resnick, 1987); (Thompson, 2008)), (Appendix 2 in Supplementary material for more details). These cognitive skills are linked to the Chemical-Engineering toolbox, in which transferable skills complement fundamental knowledge in chemical engineering academic program. Only a small selection of transferable skills is shown here: others like critical mindset, (interdisciplinary) collaboration, communication, and information literacy are listed among the “21st Century Skills” and receive much attention in the development of new courses.

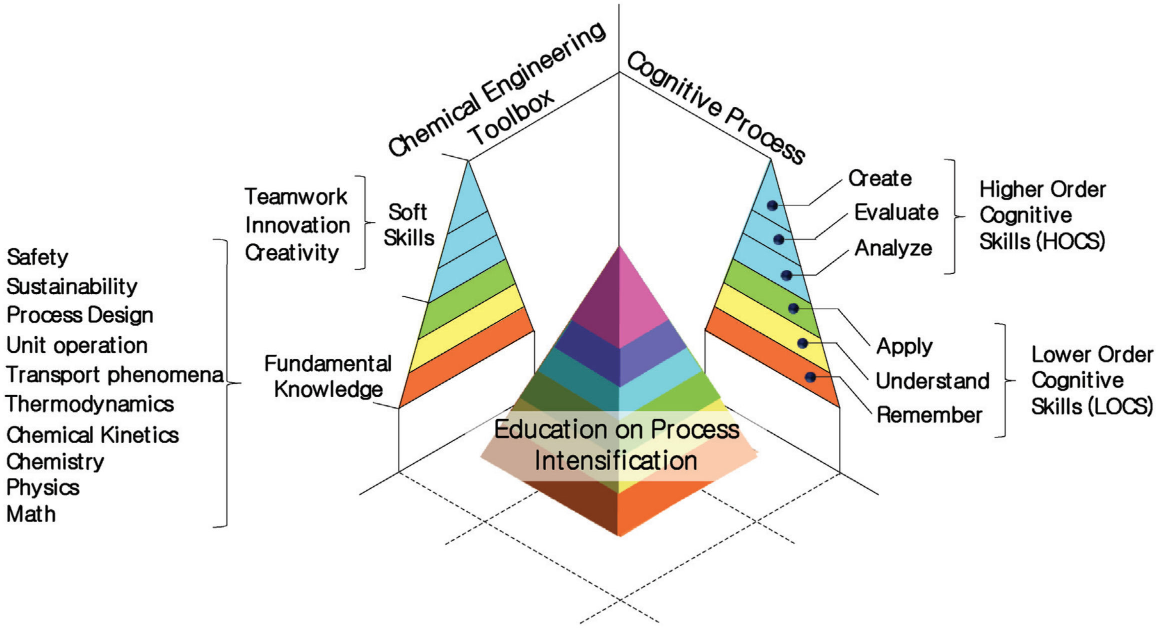

Fig. 1. Combining the chemical engineering toolbox with the cognitive process taxonomy for the development of effective teaching in PI. Arguably, this concept is valid also for a global program, PI adds synthesis (integration) to the top level.

The cognitive process taxonomy elucidates why it is virtually impossible for students to be creative if they spend most of the class time listening to an expert. Hearing an expert thinking out loud during the creative process is one essential step, but it is insufficient to enable students to do it themselves. If the main cognitive activity of students is trying to "understand", there is little room for them to rapidly apply, analyse, and evaluate in front of a competent educator. The educator in turn, must diagnose any weaknesses and the cognitive process in which they are stuck. Here, the concept of "fail fast" philosophy is particularly important for an enjoyable and effective teaching-learning process (Khanna et al., 2016). By combining Bloom's Taxonomy with the "Chemical Engineering Toolbox" required in PI, one can find at the intersection clear guidelines to build an effective educational program on PI (Fig. 1). This poses an additional challenge to the educators, as often they have not climbed the "PI ladder". We advocate that PI should be incorporated in the single technical toolbox.

Learning PI and being able to transfer the knowledge into real situations encourages students to work in circumstances as close as possible to the work-floor. This requires active learning approaches, like project-based learning, problem-based learning, team-based learning and case studies, where the students are cognitively engaged and more likely to support higher order cognitive skills (Freeman et al., 2014). If the task inspires reaching the higher levels of the cognitive processes, it will allow divergent thinking and interdisciplinarity needed for the future of industry (Connor et al., 2017). Table 1 presents typical PI learning activities and the cognitive process students potentially reach through these.

3. Challenges of teaching and deploying PI within higher education

Preparing students to join the creative and open-minded workforce requires flexibility in the university environment and learning conditions (material, flexible schedules, academic tasks, etc.). While the objective is to use PI courses as the playground for chemical engineering students to free-up their creativity and ingenuity to create, study, and validate intensified processes, in practice the crowded academic agenda limits the time of students and educators. Instructing students using more interactive strategies will increase the students' engagement. The next section focusses on three challenges to incorporate PI into existing courses: (1) finding the right educational modules in the chemical engineering curriculum to introduce and deepened PI technologies; (2) limited availability of case studies for education; and, (3) the need to prepare students with essential-skills to communicate effective techno-economic analyses of PI when working in industry.

3.1. Adequate integration of PI in established chemical engineering curriculum

During the workshop, there was a question that all participants were grappling with: where does a PI course fit in the already crowded academic curricula? Though the majority agreed that PI is more appropriate at a graduate level, it was deemed important to find ways to inspire students even at the undergraduate level, especially regarding the underlying physics of non-traditional forces, without detailed PI analyses at a higher order of cognitive skills (HOCS, Fig. 1). However, this approach faces a greater challenge nowadays at all levels. This is related to the multidisciplinary programmes that are the norm in many technical universities and tend to saturate the students with information. Does PI add to this confusion with all its novelty and definitions? We believe that the benefits of bringing at least the basic principles and comprehensive approach of PI outweigh any risk of complicating existing curricula, as long as PI can be seamlessly incorporated, either in ongoing courses, or in a new course.

An easier-to-answer question that surfaced was whether a PI course should be mandatory: unanimously, and not surprisingly, the answer was yes. This answer was accompanied by practical suggestions of progressive implementation within the overall curricula, such as mentioning PI to both undergraduate and graduate students and demonstrating examples of PI in the context of chemical reaction engineering and unit operations, as well as design projects for the students to practice and implement PI principles. It is also useful to bring practical examples that concern nature. For instance, when mentioning micro-reactors, a popular example, PI contrasts traditional microchannels and human blood vessels: a

Table 1
Examples of learning activities in PI and the required fundamental disciplines and transferable skills. Appendix 3 provides specific implementation examples of each of these learning activities where the involvement of different concepts in chemical engineering are illustrated. Further details on the examples provided in Appendix 3 can be obtained from cited references or by contacting the co-authors of this work.

Cognitive Process	PI learning activity	Chemical engineering toolbox
Create (Lucas, 2001)[1]	A group of three to five students (from more than one discipline, if possible) analyse a real problem situation, co-create an original strategy emerging from the combination of multidisciplinary frameworks. They plan how they would put it into place. Larger groups than 5 students might prove difficult to handle, and the chance of "free-riders" increases.	*Fundamental knowledge:* Safety, Sustainability, Process Design, Unit Operations, Transport Phenomena, Thermodynamics, Chemical Kinetics, Chemistry, Physics, Mathematics *Transferable skills:* Teamwork, Innovation, critical mindset and information management, creativity See Appendix 3.2, 3.3, 3.4, 3.5, 3.6, 3.7 in Supplementary material
Evaluate	A group of students analyse a real situation within their own discipline and share it with their peers so everyone understands. Together, they evaluate all the possible strategies to solve the problem and identify what would be the best option. Then, students should be able to substantiate their selection to the lecturer. Students compare a PI process or apparatus to a conventional one, listing advantages and disadvantages	*Fundamental knowledge:* Safety, Sustainability, Unit Operations, Transport Phenomena, Thermodynamics, Chemical Kinetics, Chemistry, Physics, Mathematics *Transferable skills:* Teamwork, Innovation, critical mindset and information management. See Appendix 3.1, 3.2, 3.3, 3.4, 3.6, 3.7, 3.8 and 3.9 in Supplementary material
Analyse	Students deconstruct a real situation into its components and connect the corresponding components of a relevant concept to ascertain its underlying logic and predict what would happen if we change one or more parameters to the real situation. They explain unexpected results that happened in an experiment. Students describe a PI process, break it down into its components and indicate which physical phenomena play a role.	*Fundamental knowledge:* Safety, Unit Operations, Transport Phenomena, Thermodynamics, Chemical Kinetics, Chemistry, Physics, Mathematics *Transferable skills:* Teamwork, innovation, critical mindset and information management. See Appendix 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8 and 3.9 in Supplementary material
Apply	Students can solve abstract problems using formulas provided or learned by heart. They are able to reproduce a given experiment in the lab. Students apply e.g. mass-transfer theory in a PI context, calculate the required size of an apparatus	*Fundamental knowledge:* Transport Phenomena, Thermodynamics, Chemical Kinetics, Chemistry, Physics, Mathematics *Transferable skills:* Teamwork, critical mindset See Appendix 3.0 and 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7 in Supplementary material
Understand	Students explain in their own words the influence of velocity, temperature and concentration in a chemical process. They can find examples of the presence of these phenomena in other applications. They can also recognize why (e.g.) a static mixer is an example of PI equipment.	Fundamental knowledge: Transport Phenomena, Thermodynamics, Chemical Kinetics, Chemistry, Physics, Mathematics Transferable skills: Teamwork if in team See Appendix 3.0, 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8 in Supplementary material
Remember	Students memorize formulas, material characteristics, steps of a process, concepts attributes, etc. (or any other type of rote learning). The students are able to reproduce the definition of Process Intensification when asked	Fundamental knowledge: Thermodynamics, Chemistry, Physics, Mathematics *Transferable skills:* Teamwork if in team See Appendix 3.0, 3.1, 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, 3.8 in Supplementary material

[1] According to Lucas (2001), « [c]reative people question the assumptions they are given. They see the world differently, are happy to experiment, to take risks and to make mistakes. They make unique connections often unseen by others. » (p. 138) (Lucas, 2001).

circular microchannel of $400\ \mu m$ in a microreactor delivers a specific area of ca. 15 000 m^2/m^3. Nature, however, beats engineering: our capillary veins are ca. $10\ \mu m$ in diameter, have specific areas of ca. 400 000 m^2/m^3 and (most of the time) do not clog (Van Gerven and Stankiewicz, 2009)!

Participants in the Lorentz workshop also discussed what are the minimum resources required to have a basic, undergraduate PI module within a course. First, a costless solution would be to introduce the term "process intensification" and its meaning in different mandatory courses (as it happens now with heat and mass transfer, unit-operations, safety etc.). Some basic requirements for group project-based activities, include:

- Basic infrastructure for students to meet regularly with the instructor and teaching assistants, and separately as groups.
- Access to structured course slides, success stories – some examples where it works, could be instructional videos.
- Access to literature (traditional or electronic) including journals that publish both PI theory and applications. Different specific journals are available on PI and report on both the theory and the application of PI in different fields. To be even more effective, an online database reporting companies applying PI processes should be available to students who want to analyse and understand real examples. Another valuable tool could be a collection of patents on PI technologies, and failed PI applications. In this way students will appreciate the drivers to apply PI, as well as the factors that have permitted and impeded the deployment of the technology.
- Means to compile information, storage and preparation of documents, reports, etc.
- In the case of Problem Based Learning and Challenge Based Learning (section 4.1) that require modelling activities, which are key in a PI course, the corresponding tools, e.g. Aspen Plus, COMSOL, etc. along with a teaching assistant dedicated to these activities. Instructive, learning objectives can also be reached with simpler tools such as Microsoft Excel and MATLAB to solve differential equations for flow, heat and mass transfer, reaction kinetics, etc. These tools enable design or investigation of one or more of the PI domains (structure, synergy, energy and time) at one or more of the PI scales (plant, process, particle and molecular) (Santos and Van Gerven, 2011).
- Access to RAPID's and COSMIC's webinars on both the theory and modelling (e.g. COSMIC's tutorial on ultrasound and microwaves irradiation). These webinars could be taken as an assignment (a report by a student or group of students can follow).
- Brainstorming/creative activities.
- Laboratories: ultrasound horn or bath to examine sonication processes, (Haque et al., 2017), thermogravimetric analyser (TGA), ideally with differential scanning calorimetry (TGA-DSC) capability, and even more ideally hyphenated to a mass spectrometer

(TGA-MS or TGA-DSC-MS), to investigate high-temperature reactions in real-time (Santos et al., 2012); tubular and stirred-tank reactors for batch-to-continuous and mixed-to-plug flow process transitions (Zhang et al., 2019b); in-situ analysers (e.g. particle size, infrared) for tracking in real-time unsteady reaction processes; among others possibilities.

Ultimately, the resources do not need to be expensive for the students to deepen their analysis and come up with creative or well supported ideas. More details are given in Section 5.

3.2. Industry requirements in PI education: commercial success stories

Many large scale plants have applied PI (Rivas et al., 2020): distillation plants (Kiss, 2014)(dividing-wall columns (John et al., 2008), internally heated integrated distillation (Fang et al., 2019), reactive distillations for methyl and ethyl acetate (Singh et al., 2014), and for the esterification of acetic acid (Agreda and Heise, 1990), structured reactors (e.g. selective reactive NOx reduction), rotating HiGee equipment (Cortes Garcia et al., 2017) (e.g. seawater deaerator, stripping of hypochlorous acid, CO_2 absorption), tail gas cleaning of SO_2 by means of a rotating packed bed (RPB) reactor (Darake et al., 2014), printed circuit heat exchangers (PCHE) in offshore gas treatment plants (Baek et al., 2010), and the Twister for offshore gas drying (Esmaeili, 2016). Similarly, various types of micro- and milli-reactors or equipment have been used in fine chemicals, automotive exhaust after treatment, and the pharmaceuticals industry, where numbering-up of microfluidic structures or reactors allows for production scale-up. (Kockmann et al., 2011; Modestino et al., 2016; Shen et al., 2018; Zhang et al., 2017).

There are important reasons why PI large-scale equipment and microreactors alike, are still not used more widely, and education has the potential to resolve this in part. A list of aspects we have identified can be found in Appendix 4 in Supplementary material. Implementing these examples and the theory and economic models behind theory success in PI courses, as well as courses offered to industrial staff, can accelerate PI knowledge dissemination and its implementation.

The difficulty of making a compelling case for new solutions should not be underestimated in PI education. This is about being able to tell a credible techno-economic story, to both management and senior technologists in the company for whom PI solutions are new and "different" as well, for example:

- PI technology ***U*** improves yield *X* %, reduces energy consumption by *Y* %, and lowers CAPEX and OPEX compared to conventional processes, while reducing our CO_2 footprint by Z %.
- This PI technology is different indeed, but we understand the fundamentals.

Or a believable investment risk story:

> "This new PI solution is different from conventional technology but will allow the company to reduce capital risk, make new products (unattainable with conventional technologies), reduce inventory, manage the supply chain more effectively, etc."

In Industry, timing is critical: telling the techno-economic and risk stories at the right time in the investment cycle is fundamental to have the management selecting PI over an incumbent technology. RAPID developed a student intern program that focuses on developing the next generation of leaders in PI. The Interns work on projects at RAPID member institutions that advance PI or modular processing, while simultaneously learning about the concepts virtually through PI E-learning courses and webinars. This provides students with real-world context and a value-proposition for PI. Appendix 5 in Supplementary material summarizes a historical account of past (Dutch) experience regarding PI and the industry setting.

Implementing PI technology, like any novel development requires up to a decade and includes a research phase, a pilot plant, and a demonstration unit. Training students with innovative technologies may increase the probability of adoption and reduce industry tendency to directly jump to proven technologies with a shorter implementation cycle.

Finally, overcoming these barriers requires cooperative efforts in academia, industry and certification agencies. For example, large gaps in equipment design in the fields of ultrasonic reactors, microwaves, electric and magnetic fields should be handled in academia, while production problems of the respective equipment should be handled by industry or industry-led consortia. But there are many other design problems of already introduced equipment. For some of these items there are only simple correlations. A major problem is to find out which unit operations should be studied first, that means which equipment has highest probability to penetrate the market. As there are already many theoretical analyses of potential PI strategies for a given applications, an evaluation and ranking of these in business terms (CAPEX, OPEX) and sustainability potential (energy use, raw material efficiency usage, E-factors, etc.) as undertaken in a recent study on intensified amidation processing in the pharmaceutical industry, would be welcomed by the community (Feng et al., 2019).

4. Enablers of PI education

In this section we review some of the strategies and educational technologies that can facilitate the implementation of PI education in a more effective manner and overcome the some of the aforementioned challenges.

Learning PI in chemical engineering programs should be conceived as sandbox in which students can creatively apply all their knowledge on unit operation to tackle chemical industrial problems. To foster lively discussions and brainstorming activities between students, we can leverage several learning tools and strategies.

4.1. Problem-based learning (PBL) or Challenge Based Learning (CBL)

In PBL, students analyze and discuss a real problem with an expected scope and solution, defining the academic concepts to learn (Dolmans et al., 2016). Therefore, in PBL, the focus in more on the acquisition of knowledge, rather than on its application. In CBL (not to confuse with case-based learning) students are actively engaged in a relevant and challenging problem related to a real-world context (it is an open problem, where no solution is known). CBL is more advanced than PBL as it implies that the knowledge has been already acquired, and it interprets it, rather than assimilating it, to implement solutions that answer the challenge (Hernández-de-Menéndez et al., 2019). For example, when faced with a challenge, successful groups and individuals leverage experience, harness internal and external resources, develop a plan and push forward to find a solution (Vega and Navarrete, 2019). Along the way, there is experimentation, failure, success and ultimately consequences for actions. By adding challenges to learning environments the result is urgency, passion, and ownership – ingredients often missing in schools. CBL can be structured in three cycling phases (Fig. 2): (1) an ***investigating*** phase in which students have to internalize the problem definition and diagnosis and self-study the information to solve the case; (2) ***acting*** phase that is aimed at designing, implementing, and testing the proposed

Fig. 2. Cyclic phases of Challenge Base Learning. (https://cbl.digitalpromise.org/stories/).

solutions: and (3) ***engaging*** phase in which the students leverage the interaction with the tutor and his peers to solve the problem. This strategy supports the development of knowledge acquisition in an autonomous manner, development of transferable-skills or essential-skills and life-long learning (Ruiz-Ortega et al., 2019). In this strategy, the student-tutor interaction is employed to support the problem-solving stage rather than the knowledge acquisition (KOLMOS, 1996). We report examples of how different instructors implement either PBL or CBL in Appendix 3 in Supplementary material.

4.2. *Practical experimentation*

Practical laboratories with students manipulating equipment continues to play a prominent role in the current engineering education (Chen et al., 2016)). In order to effectively create lifelong learning on PI the cookbook experimentation (Hofstein and Lunetta, 1982; Kontra et al., 2015) should be replaced by peer-instruction and collaborative learning. To successfully implement this, universities will still need to provide the infrastructure for these activities – space, materials, lab- and pilot-scale equipment-at a cost. While potentially an expensive option, buying an experimental PI setup for educational purposes can offer deeper understanding and hands-on experience for students. Experiments can be designed in which the aim is to compare the PI setup to a more conventional one and discern the benefits and drawbacks of each. Possibilities range from static mixers to reactor setups. Creative implementation of these setups in the curriculum (e.g. a spinning-disk reactor can be used to study fluid flow in one course, mass transfer processes in another and reaction kinetics in a third) can help alleviate high cost and maintenance of the apparatus.

Renting equipment is a model where it is possible not only to teach PI, but to let a company test the technology and educate its personnel. Several companies (tech suppliers) have a renting program. Similarly, the equipment could be owned by an Institute, that rents it and the company can protect its know-how of the chemistry and test the technology after some training.

4.3. *Computer-aided teaching of PI*

Computer-aided teaching can be leveraged to facilitate the learning of PI at micro- (e.g. molecular and convective transport, heat transfer, chemical reaction mechanism, etc) and macroscopic (e.g. process capital and operational costs, environmental impact, sustainability). Here, Partial Differential Equations (PDEs) can be interactively visualised to study the microscopic processes occurring in a unit of operation (e.g. the velocity, temperature and concentration changes as a function of the operating conditions. New software modules provide intuition and applicability of these fundamentals. For example, to understand the difference between diffusion and advection of chemical species (Figure A6.3.1), problem-based learning or inquiry-based learning (Belton, 2016; Glassey et al., 2013) can be used. With this methodology, one can interactively visualise how to intensify a process by modifying the geometry of the channel, the diffusion coefficient or the velocity eventually self-discovering a static mixer (Figure A6.3.2), one of the most versatile process intensified technologies (Keil, 2018; Kiss, 2016; Towler and Sinnott, 2013).

At the macroscopic scale, Process simulation (RAPID, 2020) tools can be used to help students understanding process configuration and the consequences of PI implementation through case studies and economic analysis. The main factor hindering computer simulations of PI is that current chemical process simulator software packages lack of phenomenological or even empirical models that can capture the complexity of PI processes. For instance, in the case of molecular reactors, simulations should integrate intrinsic kinetic models at a resolution of the micro-mixing scales, as well as non-conventional driving forces or heat and mass transfer rates at the reactor scale from a few to several hundred-litre volume. However, rapid advances in first-principle computational modelling promise that the software tools to simulate PI technologies may be soon available (Appendix 6.3 in Supplementary material), thus speeding up PI education and, as a consequence, its implementation at the commercial scale (Boffito and Van Gerven, 2019; Fontes, 2020; Ge et al., 2019)

More recently, advances in both machine learning algorithms and computer hardware are opening up new possibilities to identify opportunities for process control (and the needed methods to teach it) (Rio-Chanona et al., 2019). For example, Reinforcement Learning can successfully generate an optimal policy of stochastic decision problems (Petsagkourakis et al., 2020). Thus, by combining both process simulation software and data-driven techniques (Zhang et al., 2019a), the intensified process can be improved in terms of control and scheduling decisions. While, there are several tools for AI available, (e.g. MATLAB, neural network toolbox or Python-based Tensorflow/TFLearning, PyLearn2, NeuroLab, PyTorch, Caffe, and Keras), massive amounts of data collected in the vicinity of control points are insufficient for extrapolation. So, we must caution students about these seemingly robust methodologies.

4.4. *Exploiting new (visualization) technologies*

Virtual and Augmented Reality, 3D Printing, Internet of Things, Artificial Intelligence, Virtual Laboratories are considered as transformative technologies that can be leveraged to enhance PI education. Besides offering an exciting way of education, they provide flexibility for students to acquire knowledge and practice their skills at their own pace. Among the competencies that these advances foster there are spatial visualization, innovative thinking, problem solving, creativity, analysis and critical thinking: essential abilities that the workforce of the future must have, especially in PI.

Two important examples are: Virtual and Augmented Reality and 3D Printing. Virtual and Augment Reality are two related technologies. The former develops digital environments in which users can get immersed and are able to manipulate objects and interact with the space. The later, superposes virtual objects in real images that are captured through a mobile device, the idea is to improve the environment. In either case, these technologies are useful in education to develop, for example, intensified processes in a controlled manner, explore abstract concepts and study phenomena in detail. Their key characteristics are: immersion, interaction and visual realism and these can be classified as immersive, semi-immersive, and non-immersive. The positive effects of virtual reality teaching using haptic methods have been already demonstrated for learning chemical bonding. These force feedback haptic applications can also offer new opportunities for learning to students who have difficulties in understanding some subjects, which would be game changer in the application of PI on education.(Ucar et al., 2017)

5. New subjects and material to consider in PI courses

Based on our past experience in teaching PI and other subjects, as well as the outcome of the discussion of our workshop at the Lorentz Centre, we compiled a list of items to integrate into new and existing PI courses, at several cognitive levels (Fig. 1):

- Stress on thermodynamics and the concept of entropy (Appendix 3.0 in Supplementary material).
- Methodologies or steps to guide the students (and future industry workers) on when to intensify (appendix 3.1, 6.1, 6.2 in Supplementary material). In cases where the information available in academic settings is unavailable, it makes sense to motivate students to guesstimate (estimate with inadequate or insufficient information).
- Modelling, in particular new software modules to help both education and scale-up to become commercial (Appendix 6.3 in Supplementary material). Current models are limited and do not cover all PI systems, but only the most popular ones (static mixers, reactive distillation, ultrasound mixing and induction heating), while they lack more complex cases (modelling of acoustic cavitation, plasma reactors, etc.). With the advent of the Industry 4.0, we anticipate an increase in the availability of these models, which can be then in turn adopted as teaching material.
- Laboratory sessions can be very effective to practically demonstrate the relevance of intensified devices. Despite these sessions requiring dedicated resources and time, they can be rapidly implemented since some manufacturers provide ready-to-use kits, that are compatible with standard academic facilities and analytics. For example, micro-structured mixers, reactors or spinning-disc reactors efficiently demonstrate the impact of intensification on the selectivity of chemical syntheses. See some examples on renting equipment in Section 3.1c.
- Tutored projects may also be an option to help students properly understand PI concepts and apply them to more complex problems, while getting into higher cognitive levels: the time dedicated to tutored projects is also appropriate to help them becoming creative and to go beyond their current knowledge (Appendix 3.3 in Supplementary material).
- A new and important link can also be established between PI and materials (Stankiewicz and Yan, 2019), since PI is not restricted to reactor sizing/design and activation modes only. Several intensification strategies are directly related to various aspects of materials properties: thermal conductivity for heat routing, hot spots control, tortuosity and porosity for catalytic applications, etc. Other innovative solutions such as product formulations and catalysis were not considered part of PI. Materials can be formed to have “shape-selective” geometries, from the molecular to the mesoscale. It is sufficient to think of zeolites, which have cavities that are both size and shape- selective. Other properties such as super-wettability, super-hydrophobicity, magnetic and paramagnetic properties, magnetocaloric and metamaterials offer unique opportunities for PI. The developments of the new visualization technologies outlined in Section 4.4. may accelerate even more this synergy.
- New software modules for education and scale-up can help understanding transport phenomena, especially under non-conventional conditions and in case of non-traditional driving forces. The lack of pseudo-empirical correlations is one of the first challenges a student faces when transforming or scaling up/down a new chemical process (Zhang et al., 2018). Often taught as an abstract way of estimating heat and mass transfer coefficients, these equations limit the understanding and innovative aspect of process design. See appendix 6.3 in Supplementary material for an example on how to enhance mass-transfer phenomena using computer-aided simulations.

6. Opportunities for PI to fulfil its promises

To ensure industry-pull into PI solutions, there must be a clear advantage to convince companies and investors to adopt it. We believe that a realistic approach is to find a bottleneck rather than to overhaul a complete process. For example, a plant employee explains a process to a PI expert, and together they determine what the bottlenecks are, and jointly devise a solution. The feasibility of the PI options can be assessed, considering the (economic) goals of the process, and using available methods (Reay et al., 2013), which range from being familiar to obscure (Appendices 6 in Supplementary material). A traditional risk assessment must follow. Logically, this reasoning must be taught at all relevant levels to the students or workers receiving training.

There are two main sources that can be consulted for proven solutions. First, data from the IbD project on control of a number of PI processes/demos can be shown as examples of the recent successful implementation of PI.-(Janne Paaso (VTT), Risto Sarjonen (VTT), Panu Mölsä (VTT), Markku Ohenoja (OULU), Christian Adlhart (ZHAW), Andrei Honciuc (ZHAW), Tim Freeman (FREEMAN), 2017) Second, IPIC: https://kuleuvencongres.be/ipic2019/Home.

Modelling during the design of industrial process reduces time requirements. Companies tend to commission new projects to minimize risks and delays. The experts performing these simulations must have a solid education and understating of process engineering as well as computer-aided simulation techniques.

7. Conclusions and recommendations (part 2)

It is important to reach and educate all the social layers and increase the acceptability of the chemical industries by using the tight link between Process Intensification (PI) and sustainability. PI offers opportunities to achieve the United Nations Sustainable Development Goals (UN-SDG) because it offers strategies to implement technologies with remote installation and lower CAPEX than conventional processes. This applies in particular to miniaturized chemical plants (such as micro-pyrolysis or gasification units, micro-hydro or micro gas-to-liquids systems).

We believe PI has the potential to identify solutions where conventional strategies focused on step-by-step incremental process improvements fail. However, PI solutions introduce more technological and investment risk than conventional approaches. The involvement of companies in the continuous academic education is key, as well as new methods to calculate investment and assess risk, some of which we propose in this document.

A thorough analysis of the thermodynamics, kinetics, and transport in intensified processes afford new opportunities to illustrate the core precepts of chemical engineering. The multiphysics attributes that characterize most of the intensified reactors clearly introduce a non-linear behaviour for these devices. The acceleration of phenomena (fast reactions kinetics, high transfer capacities, process gain nonlinearity, etc.) also requires fast measurements and actuators to ensure stability. Furthermore, the conversion of batch processes to continuous processes necessitates drastic modifications of the control systems, as well as training for engineers.

For this reason, we consider that process control in the context of PI should receive special attention in PI education. PI-specific case studies, either integrated in the last-year chemical engineering design project, or in other courses, is an approach that most of the participants of the workshop recommend (see Appendices in Supplementary material), and that students seem to enjoy. Exposing all of the students to PI already at the undergraduate levels, increases the opportunity of them to propose PI solutions in the future in the industrial context they will work on.

We believe that this work, together with Part 1, will pave the way to a more efficient adoption of education on PI, and hopefully a faster implementation in the industry.

References cited in the Supplementary material

Anderson and Krathwohl (2001), Andresen (2011), Charpentier (2010), Chen et al. (2015), Crooks (2007), Denbigh (1951), Durmayaz (2004), Feng et al. (2017), Ghanem et al. (2014), Janne Paaso (2017), Kingston and Razzitte (2017), Kockmann et al. (2017), Law et al. (2017), Leites et al. (2003), Lieberman (1989), Livotov (2019), Livotov et al. (2019), Livotov and Petrov (2013), Milanovic and Eppes (2016), Missen et al. (1998), Navarro-Brull et al. (2019), Noel (2019), Patience and Boffito (2020), Reay (1991), Rivas et al. (2018), ROSJORDE et al. (2007), Stankiewicz and Moulijn (2002), Torabi et al. (2019), Tribe and Alpine (1986), Weber and Snowden-Swan (2019), Wright (1936).

Declaration of Competing Interest

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ece.2020.05.001.

References

ABET, 2017. ABET Engineering Accreditation Commission: Criteria for Accrediting Engineering Programs [WWW Document].

Agreda, V.H., Heise, W.H., 1990. High-purity methyl acetate via reactive distillation. Chem. Eng. Prog. 86, 40–46.

Anderson, L.W., Krathwohl, D.R., 2001. A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives. Longman, New York.

Andresen, B., 2011. Current trends in finite-time thermodynamics. Angew. Chemie Int. Ed. 50, 2690–2704, http://dx.doi.org/10.1002/anie.201001411.

Ausfelder, F., Hanna Ewa, D., 2018. OPTIONEN FÜR EIN NACHHALTIGES ENERGIESYSTEM MIT POWER-TO-X TECHNOLOGIEN [WWW Document].

Baek, S., Kim, J., Jeong, S., 2010. Micro channel heat exchanger for LNG-FPSO application. Ninth ISOPE Pacific/Asia Offshore Mech. Symp.

Belton, D.J., 2016. Teaching process simulation using video-enhanced and discovery/inquiry-based learning: methodology and analysis within a theoretical framework for skill acquisition. Educ. Chem. Eng. 17, 54–64, http://dx.doi.org/10.1016/j.ece.2016.08.003.

Bloom, B.S., 1956. Taxonomy of educational objectives. Cognitive Domain, Vol. 1. McKay, New York.

Boffito, D.C., Van Gerven, T., 2019. Process intensification and catalysis. Ref. Modul. Chem. Mol. Sci. Chem. Eng., http://dx.doi.org/10.1016/B978-0-12-409547-2.14343-4.

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int. J. Life Cycle Assess. 23, 368–378, http://dx.doi.org/10.1007/s11367-017-1333-8.

CEFIC, DECHEMA, 2017. CEFIC Report Low Carbon Energy and Feedstock for the European Chemical Industry.

Charpentier, J.-C., 2010. Among the trends for a modern chemical engineering, the third paradigm: the time and length multiscale approach as an efficient tool for process intensification and product design and engineering. Chem. Eng. Res. Des. 88, 248–254, http://dx.doi.org/10.1016/j.cherd.2009.03.008.

Chen, Y., Sabio, J.C., Hartman, R.L., 2015. When solids stop flow chemistry in commercial tubing. J. Flow Chem. 5, 166–171, http://dx.doi.org/10.1556/1846.2015.00001.

Chen, W., Shah, U., Brechtelsbauer, C., 2016. The discovery laboratory – a student-centred experiential learning practical: part I – overview. Educ. Chem. Eng. 17, 44–53, http://dx.doi.org/10.1016/j.ece.2016.07.005.

Connor, A., Sosa, R., Jackson, A.G., Marks, S., 2017. Problem solving at the edge of disciplines. In: Zhou, C. (Ed.), Handbook of Research on Creative Problem-Solving Skill Development in Higher Education. Hershey PA, pp. 212–234, http://dx.doi.org/10.4018/978-1-5225-0643-0.ch010.

Cortes Garcia, G.E., van der Schaaf, J., Kiss, A.A., 2017. A review on process intensification in HiGee distillation. J. Chem. Technol. Biotechnol. 92, 1136–1156, http://dx.doi.org/10.1002/jctb.5206.

Crooks, G.E., 2007. Measuring thermodynamic length. Phys. Rev. Lett. 99, 100602, http://dx.doi.org/10.1103/PhysRevLett.99.100602.

Darake, S., Rahimi, A., Hatamipour, M.S., Hamzeloui, P., 2014. SO 2 removal by seawater in a packed–bed tower: experimental study and mathematical modeling. Sep. Sci. Technol. 49, 988–998, http://dx.doi.org/10.1080/01496395.2013.872660.

Denbigh, K.G., 1951. The Thermodynamics of the Steady State. Methuen & Co. & John Wiley.

Dolmans, Diana H.J.M., Loyens, S.M.M., Marcq, H., Gijbels, D., 2016. Deep and surface learning in problem-based learning: a review of the literature. Adv. Heal. Sci. Educ. 21, 1087–1112, http://dx.doi.org/10.1007/s10459-015-9645-6.

Durmayaz, A., 2004. Optimization of thermal systems based on finite-time thermodynamics and thermoeconomics. Prog. Energy Combust. Sci. 30, 175–217, http://dx.doi.org/10.1016/j.pecs.2003.10.003.

EFCE, 2018. The Second International Process Intensification Conference [WWW Document] (Accessed 2.4.20) https://kuleuvencongres.be/ipic2019/Home.

Esmaeili, A., 2016. Supersonic separation of natural gas liquids by twister technology. Chem. Eng. Trans. 52, 7–12, http://dx.doi.org/10.3303/CET1652002.

Fang, J., Cheng, X., Li, Z., Li, H., Li, C., 2019. A review of internally heat integrated distillation column. Chin. J. Chem. Eng. 27, 1272–1281, http://dx.doi.org/10.1016/j.cjche.2018.08.021.

Feng, R., Ramchandani, S., Ramalingam, B., Tan, S.W.B., Li, C., Teoh, S.K., Boodhoo, K., Sharratt, P., 2017. Intensification of continuous ortho-lithiation at ambient conditions—process understanding and assessment of sustainability benefits. Org. Process Res. Dev. 21, 1259–1271, http://dx.doi.org/10.1021/acs.oprd.7b00142.

Feng, R., Ramchandani, S., Salih, N.M., Lim, X.Y.E., Tan, S.W.B., Lee, L.Y., Teoh, S.K., Sharratt, P., Boodhoo, K., 2019. Process intensification strategies and sustainability analysis for amidation processing in the pharmaceutical industry. Ind. Eng. Chem. Res. 58, 4656–4666, http://dx.doi.org/10.1021/acs.iecr.8b04063.

Fontes, E., 2020. Modeling Approaches in Heterogeneous Catalysis [WWW Document]. Comsol log.

Freeman, S., Eddy, S.L., McDonough, M., Smith, M.K., Okoroafor, N., Jordt, H., Wenderoth, M.P., 2014. Active learning increases student performance in science, engineering, and mathematics. Proc. Natl. Acad. Sci. 111, 8410–8415, http://dx.doi.org/10.1073/pnas.1319030111.

Ge, W., Guo, L., Liu, X., Meng, F., Xu, J., Huang, W.L., Li, J., 2019. Mesoscience-based virtual process engineering. Comput. Chem. Eng. 126, 68–82, http://dx.doi.org/10.1016/j.compchemeng.2019.03.042.

Ghanem, A., Lemenand, T., Della Valle, D., Peerhossaini, H., 2014. Static mixers: mechanisms, applications, and characterization methods – a review. Chem. Eng. Res. Des. 92, 205–228, http://dx.doi.org/10.1016/j.cherd.2013.07.013.

Glassey, J., Novakovic, K., Parr, M., 2013. Enquiry based learning in chemical engineering curriculum supported by computer aided delivery. Educ. Chem. Eng. 8, e87–e93, http://dx.doi.org/10.1016/j.ece.2013.06.003.

Haque, F., Dutta, A., Thimmanagari, M., Chiang, Y.W., 2017. Integrated Haematococcus pluvialis biomass production and nutrient removal using bioethanol plant waste effluent. Process Saf. Environ. Prot. 111, 128–137, http://dx.doi.org/10.1016/j.psep.2017.06.013.

Henriksen, D., Mehta, R., Mehta, S., 2019. Design thinking gives STEAM to teaching: a framework that breaks disciplinary boundaries. In: STEAM Education. Springer International Publishing, Cham, pp. 57–78, http://dx.doi.org/10.1007/978-3-030-04003-1_4.

Hernández-de-Menéndez, M., Vallejo Guevara, A., Tudón Martínez, J.C., Hernández Alcántara, D., Morales-Menendez, R., 2019. Active learning in engineering education. A review of fundamentals, best practices and experiences. Int. J. Interact. Des. Manuf. 13, 909–922, http://dx.doi.org/10.1007/s12008-019-00557-8.

Hofstein, A., Lunetta, V.N., 1982. The role of the laboratory in science teaching: neglected aspects of research. Rev. Educ. Res. 52, 201–217, http://dx.doi.org/10.3102/00346543052002201.

Institution of Chemical Engineers (IChemE), 2019. Accreditation of Chemical Engineering Programmes: a Guide for Higher Education Providers and Assessors [WWW Document].

Janne Paaso (VTT), Risto Sarjonen (VTT), Panu Mölsä (VTT), Markku Ohenoja (OULU), Christian Adlhart (ZHAW), Andrei Honciuc (ZHAW), Tim Freeman (FREEMAN), C.R. (Tel-T., 2017. Intensified by Design© for the intensification of processes involving solids handling.

John G. Pendergast, David Vickery, Patrick Au-Yeung, Joe Anderson, The Dow Chemical Company Dec 19 2008, Consider Dividing Wall Columns. https://www.chemicalprocessing.com/articles/2008/245/.

Keil, F.J., 2018. Process intensification. Rev. Chem. Eng. 34, 135–200, http://dx.doi.org/10.1515/revce-2017-0085.

Khanna, R., Guler, I., Nerkar, A., 2016. Fail often, fail big, and fail fast? Learning from small failures and R&D performance in the pharmaceutical industry. Acad. Manage. J. 59, 436–459, http://dx.doi.org/10.5465/amj.2013.1109.

Kingston, D., Razzitte, A.C., 2017. Entropy production in chemical reactors. J. Non-Equilibrium Thermodyn. 42, http://dx.doi.org/10.1515/jnet-2016-0066.

Kiss, A.A., 2014. Distillation technology - still young and full of breakthrough opportunities. J. Chem. Technol. Biotechnol. 89, 479–498, http://dx.doi.org/10.1002/jctb.4262.

Kiss, A.A., 2016. Process intensification: industrial applications. In: Process Intensification in Chemical Engineering. Springer International Publishing, Cham, pp. 221–260, http://dx.doi.org/10.1007/978-3-319-28392-0_8.

Klemeš, Jiří Jaromír, et al., 2020. S. In: ustainable Process Integration and Intensification: Saving Energy, Water and Resources. Walter de Gruyter GmbH & Co KG, 2018.

Kockmann, N., Gottsponer, M., Roberge, D.M., 2011. Scale-up concept of single-channel microreactors from process development to industrial production. Chem. Eng. J. 167, 718–726, http://dx.doi.org/10.1016/j.cej.2010.08.089.

Kockmann, N., Thenée, P., Fleischer-Trebes, C., Laudadio, G., Noël, T., 2017. Safety assessment in development and operation of modular continuous-flow processes. React. Chem. Eng. 2, 258–280, http://dx.doi.org/10.1039/C7RE00021A.

Kolmos, A., 1996. Reflections on project work and problem-based learning. Eur. J. Eng. Educ. 21, 141–148, http://dx.doi.org/10.1080/03043799608923397.

Kontra, C., Lyons, D.J., Fischer, S.M., Beilock, S.L., 2015. Physical experience enhances science learning. Psychol. Sci. 26, 737–749, http://dx.doi.org/10.1177/0956797615569355.

Law, R., Ramshaw, C., Reay, D., 2017. Process intensification – overcoming impediments to heat and mass transfer enhancement when solids are present, via the IbD project. Therm. Sci. Eng. Prog. 1, 53–58, http://dx.doi.org/10.1016/j.tsep.2017.02.004.

Leites, I.L., Sama, D.A., Lior, N., 2003. The theory and practice of energy saving in the chemical industry: some methods for reducing thermodynamic irreversibility in chemical technology processes. Energy 28, 55–97, http://dx.doi.org/10.1016/S0360-5442(02)00107-X.

Lieberman, M.B., 1989. The learning curve, technology barriers to entry, and competitive survival in the chemical processing industries. Strateg. Manage. J. 10, 431–447, http://dx.doi.org/10.1002/smj.4250100504.

Livotov, P., 2019. Enhancing innovation and entrepreneurial competences of engineering students through a systematic cross-industry innovation learning course. 29th Annual Conf. of the Australasian Association for Engineering Education.

Livotov, P., Petrov, V., 2013. TRIZ innovation technology. In: Product Development and Inventive Problem Solving. Handbook.

Livotov, P., Chandra Sekaran, A.P., Mas'udah, Law, R., Reay, D., Sarsenova, A., Sayyareh, S., 2019. Eco-innovation in process engineering: contradictions, inventive principles and methods. Therm. Sci. Eng. Prog. 9, 52–65, http://dx.doi.org/10.1016/j.tsep.2018.10.012.

Lucas, B., 2001. Creative teaching, teaching creativity and creative learning. In: Craft, Anna, Bob Jeffrey, M.L. (Eds.), Creativity in Education. , pp. 35–44.

Madden, M.E., Baxter, M., Beauchamp, H., Bouchard, K., Habermas, D., Huff, M., Ladd, B., Pearon, J., Plague, G., 2013. Rethinking STEM education: an interdisciplinary STEAM curriculum. Procedia Comput. Sci. 20, 541–546, http://dx.doi.org/10.1016/j.procs.2013.09.316.

Milanovic, I., Eppes, T., 2016. Application building in undergraduate courses with a simulation component. Fora: Advances in Fluids Engineering Education; Cavitation and Multiphase Flow; Fluid Measurements and Instrumentation, Volume 2. American Society of Mechanical Engineers, http://dx.doi.org/10.1115/FEDSM2016-7844.

Missen, R.W., Mims, C.A., Saville, B.A., 1998. Introduction to Chemical Reaction Engineering and Kinetics. John Wiley & Sons, New York.

Modestino, M.A., Fernandez Rivas, D., Hashemi, S.M.H., Gardeniers, J.G.E., Psaltis, D., 2016. The potential for microfluidics in electrochemical energy systems. Energy Environ. Sci. 9, 3381–3391, http://dx.doi.org/10.1039/C6EE01884J.

Navarro-Brull, F.J., Teixeira, A.R., Giri, G., Gómez, R., 2019. Enabling low power acoustics for capillary sonoreactors. Ultrason. Sonochem. 56, 105–113, http://dx.doi.org/10.1016/j.ultsonch.2019.03.013.

Noel, T., 2019. A Change of Art [WWW Document] (Accessed 2.10.20) https://www.chemistryworld.com/opinion/flow-into-the-chemistry-curriculum/4010382.article#/.

Patience, G.S., Boffito, D.C., 2020. Distributed production: scale-up versus experience. J. Adv. Manuf. Process., http://dx.doi.org/10.1002/amp2.10039.

Petsagkourakis, P., Sandoval, I.O., Bradford, E., Zhang, D., del Rio-Chanona, E.A., 2020. Reinforcement learning for batch bioprocess optimization. Comput. Chem. Eng. 133, 106649, http://dx.doi.org/10.1016/j.compchemeng.2019.106649.

RAPID, n.d. Training & Education [WWW Document].

Reay, D., 1991. Heat transfer enhancement—a review of techniques and their possible impact on energy efficiency in the U.K. Heat Recovery Syst. CHP 11, 1–40, http://dx.doi.org/10.1016/0890-4332(91)90185-7.

Reay, D., Ramshaw, C., Harvey, A., 2013. Process Intensification, 2nd edition. Elsevier.

Resnick, L.B., 1987. Education and Learning to Think. National Academies Press.

Rio-Chanona, E.A., Wagner, J.L., Ali, H., Fiorelli, F., Zhang, D., Hellgardt, K., 2019. Deep learning-based surrogate modeling and optimization for microalgal biofuel production and photobioreactor design. AIChE J. 65, 915–923, http://dx.doi.org/10.1002/aic.16473.

Rivas, D.F., Castro-Hernández, E., Villanueva Perales, A.L., van der Meer, W., 2018. Evaluation method for process intensification alternatives. Chem. Eng. Process. - Process Intensif. 123, 221–232, http://dx.doi.org/10.1016/j.cep.2017.08.013.

Rivas, D.F., Boffito, D.C., Faria-Albanese, J., Glassey, J., Afraz, N., Henk, A., Boodhoo, K.V.K., Bos, R., Cantin, J., Chiang, Y.W. (Emily), Commenge, J.-M., Dubois, J.-L., Galli, F., Gueneau de Mussy, J.P., Harmsen, J., Kalra, S., Keil, F., Morales-Mendenez, R., Navarro-Brull, F.J., Noël, T., Ogden, K., Patience, G., Reay, D., Santos, R.M., Smith-Schoettker, A., Stankiewicz, A.I., Berg, H. van den, Gerven, T. van, Gestel, J. van, Stelt, M. van der, Ve, M. van de, Weber, R.S., 2020. Process intensification education contributes to sustainable development goals. Part 1. Educ. Chem. Eng.

Rosjorde, A., Kjelstrup, S., Johannessen, E., Hansen, R., 2007. Minimizing the entropy production in a chemical process for dehydrogenation of propane. Energy 32, 335–343, http://dx.doi.org/10.1016/j.energy.2006.07.013.

Ruiz-Ortega, A.M., Gallardo-Rodríguez, J.J., Navarro-López, E., Cerón-García, M., del, C., 2019. Project-led-education experience as a partial strategy in first years of engineering courses. Educ. Chem. Eng. 29, 1–8, http://dx.doi.org/10.1016/j.ece.2019.05.004.

Santos, R.M., Van Gerven, T., 2011. Process intensification routes for mineral carbonation*. Greenh. Gases Sci. Technol. 1, 287–293, http://dx.doi.org/10.1002/ghg.36.

Santos, R.M., Ling, D., Sarvaramini, A., Guo, M., Elsen, J., Larachi, F., Beaudoin, G., Blanpain, B., Van Gerven, T., 2012. Stabilization of basic oxygen furnace slag by hot-stage carbonation treatment. Chem. Eng. J. 203, 239–250, http://dx.doi.org/10.1016/j.cej.2012.06.155.

Shen, Q., Zhang, C., Tahir, M.F., Jiang, S., Zhu, C., Ma, Y., Fu, T., 2018. Numbering-up strategies of micro-chemical process: uniformity of distribution of multiphase flow in parallel microchannels. Chem. Eng. Process. - Process Intensif. 132, 148–159, http://dx.doi.org/10.1016/j.cep.2018.09.002.

Singh, D., Gupta, R.K., Kumar, V., 2014. Experimental studies of industrial-scale reactive distillation finishing column producing ethyl acetate. Ind. Eng. Chem. Res. 53, 10448–10456, http://dx.doi.org/10.1021/ie404443g.

Stankiewicz, A., Moulijn, J.A., 2002. Process intensification. Ind. Eng. Chem. Res. 41, 1920–1924, http://dx.doi.org/10.1021/ie011025p.

Stankiewicz, A.I., Yan, P., 2019. 110th anniversary: the missing link unearthed: materials and process intensification. Ind. Eng. Chem. Res. 58, 9212–9222, http://dx.doi.org/10.1021/acs.iecr.9b01479.

Stork, M., de Beer, J., Lintmeijer, N., den, O.B., 2018. Roadmap for the Dutch chemical industry towards 2050 [WWW document]. Chem. Clim.

United Nations Sustainable Development, https://sustainabledevelopment.un.org. Date accessed: 2020-03-31.

Thompson, T., 2008. Mathematics teachers' interpretation of HIGHER-ORDER thinking in BLOOM'S taxonomy. Int. Electron. J. Math. Educ. 3, 96–109.

Torabi, M., Karimi, N., Ghiaasiaan, M., Wongwises, S., 2019. Non-equilibrium thermodynamics of Micro technologies. Entropy 21, 501, http://dx.doi.org/10.3390/e21050501.

Towler, G., Sinnott, R., 2013. Design of reactors and mixers. In: Chemical Engineering Design. Elsevier, pp. 631–751, http://dx.doi.org/10.1016/B978-0-08-096659-5.00015-8.

Tribe, M.A., Alpine, R.L.W., 1986. Scale economies and the "0.6 rule". Eng. Costs Prod. Econ. 10, 271–278, http://dx.doi.org/10.1016/0167-188X(86)90053-4.

Ucar, E., Ustunel, H., Civelek, T., Umut, I., 2017. Effects of using a force feedback haptic augmented simulation on the attitudes of the gifted students towards studying chemical bonds in virtual reality environment. Behav. Inf. Technol. 36, 540–547, http://dx.doi.org/10.1080/0144929X.2016.1264483.

Van Gerven, T., Stankiewicz, A., 2009. Structure, energy, synergy, time-the fundamentals of process intensification. Ind. Eng. Chem. Res. 48, 2465–2474, http://dx.doi.org/10.1021/ie801501y.

Vega, F., Navarrete, B., 2019. Professional design of chemical plants based on problem-based learning on a pilot plant. Educ. Chem. Eng. 26, 30–34, http://dx.doi.org/10.1016/j.ece.2018.08.001.

Weber, R.S., Snowden-Swan, L.J., 2019. The economics of numbering up a chemical process enterprise. J. Adv. Manuf. Process. 1, e10011, http://dx.doi.org/10.1002/amp2.10011.

Wright, T.P., 1936. Factors affecting the cost of airplanes. J. Aeronaut. Sci. 3, 122–128, http://dx.doi.org/10.2514/8.155.

Zhang, J., Wang, K., Teixeira, A.R., Jensen, K.F., Luo, G., 2017. Design and scaling up of microchemical systems: a review. Annu. Rev. Chem. Biomol. Eng. 8, 285–305, http://dx.doi.org/10.1146/annurev-chembioeng-060816-101443.

Zhang, L., Fung, K.Y., Wibowo, C., Gani, R., 2018. Advances in chemical product design. Rev. Chem. Eng. 34, 319–340, http://dx.doi.org/10.1515/revce-2016-0067.

Zhang, D., Del Rio-Chanona, E.A., Petsagkourakis, P., Wagner, J., 2019a. Hybrid physics-based and data-driven modeling for bioprocess online simulation and optimization. Biotechnol. Bioeng. 116, 2919–2930, http://dx.doi.org/10.1002/bit.27120.

Zhang, N., Santos, R.M., Smith, S.M., Šiller, L., 2019b. Acceleration of CO2 mineralisation of alkaline brines with nickel nanoparticles catalysts in continuous tubular reactor. Chem. Eng. J. 377, 120479, http://dx.doi.org/10.1016/j.cej.2018.11.177.