Process Intensification education contributes to sustainable development goals. Part 2


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Process Intensification education contributes to sustainable development goals. Part 2


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Graphical Abstract

Highlights
- (Each Highlight can be no more than 85 characters, including spaces)
- Teaching Process intensification (PI) is important to reach sustainable development goals
- An educational strategy in the framework of PI is expanded
- Examples of education activities related to PI are presented
- PI available courses (in academy and industry) are listed
- An efficient adoption of education on PI, and faster implementation in the industry is envisaged

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 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 DEHEMA, 2017; Stork M., de Beer J., Lintmeijer N., 2018), 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 70s 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 (Fernandez 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 (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 Figure 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 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.

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 (Figure 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.

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 these present work.
Create (Lucas, 2001)  
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

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

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.

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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)
| 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 |
| 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 |
| 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 |

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, Figure 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 circular microchannel of 400 µm in a microreactor delivers a specific area of ca. 15 000 m²/m³. Nature, however, beats engineering: our capillary veins are ca. 10 µm in diameter, have specific areas of ca. 400 000 m²/m³ 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, some demos also but that could be with 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., 2019); 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 G. Pendergast, David Vickery, 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, CO2 absorption), tail gas cleaning of SO2 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. 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 CO₂ 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 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 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 is 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 (Figure 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 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.

**Figure 2.** Cyclic phases of Challenge Base Learning. ([https://cbl.digitalpromise.org/stories/](https://cbl.digitalpromise.org/stories/))

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 life-long 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, n.d.) 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), 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 (D. Zhang et al., 2019), 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 latter, 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 (Figure 1):

- Stress on thermodynamics and the concept of entropy (Appendix 3.0).
- Methodologies or steps to guide the students (and future industry workers) on when to intensify (appendix 3.1, 6.1, 6.2). 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). 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 3.1 c.
- 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).
- 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 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). 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 Mõlsä (VTT), Markku Ohenoja (OULU), Christian Adlhart (ZHAV), Andrei Honciuc (ZHAV), Tim Freeman (FREEMAN), 2017) Second, IPIC: https://kuleuwencongres.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 understanding of process engineering as well as computer-aided simulation techniques.

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 affords 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), 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.

**Conflicts of Interest**

There are no conflicts to declare.

**Acknowledgments**

The authors thank the Lorentz Centre for hosting this workshop (Educating on Process Intensification) and all attendees of the workshop for their invaluable input, vision for process intensification technologies, and candid discussions. We are also grateful to other participants who voluntarily are not co-authors of this manuscript: M. Goes (TKI Chemie), P. Huizenga (Shell), J.P. Gueneau de Mussy (KU Leuven), C. Picioreanu (TU Delft), E. Schaer (Univ. Lorraine), Mark van de Ven (National Institute for Public Health and the Environment (RIVM), The Netherlands).

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### Appendix 1. Current and past courses

**Utrecht University of Applied Sciences**

<table>
<thead>
<tr>
<th>Course name</th>
<th>Instructor(s)</th>
<th>Credits / Level</th>
<th>Editions / # students</th>
<th>Position in the degree</th>
<th>Resources used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Technology</td>
<td>B. Broeze</td>
<td>5 BSc</td>
<td>In development for start in 2020-21</td>
<td>Third year, semester 2</td>
<td>Theory and experiment, focus on differences between conventional and novel reactors, hands-on experience with SpinPro reactor and/or microreactor</td>
</tr>
<tr>
<td>Process Design</td>
<td>M. van der Stelt</td>
<td>10 BSc</td>
<td>In development for start in 2020-21</td>
<td>Third year, semester 2</td>
<td>Process design, (example of Problem Based Learning) designing and contrasting a conventional process and a sustainable one, identifying advantages and disadvantages.</td>
</tr>
<tr>
<td>Project Process Optimization</td>
<td>J. Hamerlinck, H. Bollemaat, J. van Gestel et al.</td>
<td>10 BSc</td>
<td>2016-17 – 30 2017-18 – 35 2018-19 – 35 Course active since 10+ years</td>
<td>Third year, Semester 2</td>
<td>In-company research project (example of Problem Based Learning): a group of three third-year students work on a real technological (optimisation) problem, on location at the company that supplied the research problem. Several successful projects over the</td>
</tr>
</tbody>
</table>
past years have been specifically PI-themed. At the end of the project, the students present and defend their conclusions in an oral presentation at the company, as well as in a written report. The evaluation requires the students to function at the “Analyse” and “Evaluate” levels of the taxonomy presented in Figure 1. See Appendix 3.6 for a more extensive description.

| Other | The courses are open to students with prior knowledge of basic chemical & process engineering (e.g. BSc Process Technology course); heat and mass transfer and with internship experience. Students are introduced to sustainability in their first semester, and to PI as a concept in the third and fourth semesters. All chemical-engineering students follow these courses. While the program has no specific “PI course” as such, these are the courses in which PI is given ample attention and students are expected to apply the concepts. Sustainability, economical and process safety concerns are incorporated into the curriculum in this part, especially in the Plant Design course. |

University of Twente (active courses in bold)
<table>
<thead>
<tr>
<th>Course name</th>
<th>Credits / Level</th>
<th>Editions / # students</th>
<th>Position in the degree</th>
<th>Resources used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Intensification Principles</td>
<td>5 MSc</td>
<td>2015-16 / 34 2016-17 / 47 2017-18 / 50</td>
<td>First year, Semester 1</td>
<td>Problem-based learning (PBL) around a project, using flipped classroom for 55% of the time. Students receive basic elements of PI and entrepreneurship. Work in groups related to existing equipment, company or academic example. Research articles, optional books, instructional videos, etc.</td>
</tr>
<tr>
<td>Innovating Reactor Systems</td>
<td>2.5 MSc</td>
<td>2019-20 / 18</td>
<td>First year, Semester 1</td>
<td></td>
</tr>
<tr>
<td>D. Fernandez Rivas</td>
<td></td>
<td></td>
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</tbody>
</table>

Other
Students from two different Chemical Engineering study tracks follow it: Materials and Process; also, Advanced Technologies, and other disciplines.
In the course evaluation, about 50% of students felt they had received some similar concepts in courses such as Process Design, and Entrepreneurial-related courses in their BSc. Not all students felt comfortable with the challenge of “playing the role” of small spin-off, due to their expectations to work in large companies after graduation.
Appendices 3.2 and 3.3.
<table>
<thead>
<tr>
<th>Instructor(s)</th>
<th>/ # students</th>
<th>Elective in the MSc curriculum</th>
<th>Theoretical lectures on the transport phenomena in microreactors + examples of the chemistry (Photochemistry, Electrochemistry, gas-liquid reactions) + students also select a topical paper. Write a 5-page summary on the topic and present it to the class room.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro Flow Chemistry and Process Technology</td>
<td>5 MSc</td>
<td>On average between 50-70 students</td>
<td></td>
</tr>
<tr>
<td>T. Noel (since 2018; before course was given by V. Hessel since 2010)</td>
<td></td>
<td>Elective in the MSc curriculum</td>
<td>Theoretical lectures on the transport phenomena in microreactors + examples of the chemistry (Photochemistry, Electrochemistry, gas-liquid reactions) + students also select a topical paper. Write a 5-page summary on the topic and present it to the class room.</td>
</tr>
<tr>
<td>Other</td>
<td>Mainly followed by students in the process technology track but also few students from the molecular organic chemistry track select the course.</td>
<td></td>
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</tr>
</tbody>
</table>
### School of Engineering at the University of Guelph

<table>
<thead>
<tr>
<th>Course name Instructor(s)</th>
<th>Credits / Level</th>
<th>Editions / # students</th>
<th>Position in the degree</th>
<th>Resources used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Intensification</td>
<td>E. Chiang</td>
<td>2014-2015/17 2015-2016/5 2016-2017/9 2017-2018/14 2019-2020/12</td>
<td>This is a graduate level course that is available for M. Eng, MASc, and PhD students to take.</td>
<td>Preliminary PI design projects that related to the students’ research topic are the final goal of the course. Students are encouraged to identify problems/bottlenecks of existing industry/research processes on their own, and then select, evaluate and implement suitable process intensification technologies to address the problem.</td>
</tr>
<tr>
<td><strong>Other</strong></td>
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</table>

- Students with diverse backgrounds including: chemical, biological, environmental and mechanical engineering, etc.
- Environmental, sustainability and process safety concerns are incorporated into the curriculum in this part. This is to equip students with critical thinking skills enabling them to challenge “status quo”, and hoping they will carry on this practice in their workplace.
- Process intensification technologies in structural, temporal, energy and synergy domains are introduced and discussed so that the students are familiar with the fundamentals, and the characteristics of each PI domain and relevant technologies. In 2019/2020 academic year, process safety and a new PI domain – materials, were added to the course content. One interesting observation often seen in students’ design projects is that several cycles of design iterations are needed before a feasible PI technology can be chosen.

*Delft University*
<table>
<thead>
<tr>
<th>Course name Instructor(s)</th>
<th>Credits / Level</th>
<th>Editions / # students</th>
<th>Position in the degree</th>
<th>Resources used</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.I. Stankiewicz</td>
<td>5 MSc</td>
<td>2016-17 – 70+</td>
<td>First year, Semester 2</td>
<td>There are three (3) main course contents: 1) Introduction to PI; 2) How to design a sustainable, inherently safer processing plant (presentation of PI case study assignments, See Appendix 3.10); 3. PI Approaches. The series of lectures given in Q3, while in Q4 groups of students work on a case-study and develop conceptual design of an intensified chemical plant. Book &quot;Fundamentals of Process Intensification&quot; by A. Stankiewicz, T. van Gerven and G. Stefanidis</td>
</tr>
<tr>
<td>Course active since 15+ years</td>
<td></td>
<td></td>
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<tr>
<td>Other</td>
<td>The course is open to students with prior knowledge of basic chemical &amp; process engineering (e.g. BSc Process Technology course); heat and mass transfer.</td>
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</tr>
<tr>
<td>Course name and Instructor(s)</td>
<td>Credits / Level</td>
<td>Editions / # students</td>
<td>Position in the degree</td>
<td>Resources used</td>
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</table>

**Other**

Create: Students propose a suitable technology to address the most important bottlenecks of a current process. They indicate what more is needed to further test the suitability of the process and bring it to a level of potential application.

Evaluate: Students further develop a shortlist of 2-3 technologies and, after a full analysis, evaluate which technology would be most suitable.

Analyse: Students deconstruct an existing flow sheet into bottlenecks, identify criteria to assess success, propose technologies that address the bottlenecks and rank them in terms...
of their potential success. They do this by filling in a decision matrix and to come to a shortlist of 2-3 potential technologies.

Apply: Students can reconstruct the current flow sheets and process conditions. From there, they can identify the current bottlenecks in the process, and rank them in terms of importance.

Understand: Students should understand the particular process (flow sheet, process conditions) at hand. Not all information is supplied to the students, so they should look up things themselves, calculate, or make educated guesses.

Remember: No memorization is asked for in the course. Rather, the instructor teaches the approach to identify bottlenecks and think of solutions to address these bottlenecks. This approach is what the student should “remember”.

<table>
<thead>
<tr>
<th>of their potential success. They do this by filling in a decision matrix and to come to a shortlist of 2-3 potential technologies.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apply: Students can reconstruct the current flow sheets and process conditions. From there, they can identify the current bottlenecks in the process, and rank them in terms of importance.</td>
</tr>
<tr>
<td>Understand: Students should understand the particular process (flow sheet, process conditions) at hand. Not all information is supplied to the students, so they should look up things themselves, calculate, or make educated guesses.</td>
</tr>
<tr>
<td>Remember: No memorization is asked for in the course. Rather, the instructor teaches the approach to identify bottlenecks and think of solutions to address these bottlenecks. This approach is what the student should “remember”.</td>
</tr>
<tr>
<td>Course name</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>RAPID’s Fundamentals of Process Intensification eLearning course; Instructor Jim Bielenberg, former RAPID CTO</td>
</tr>
<tr>
<td>Coming in 2020: RAPID’s Intensified Reaction Processes; Instructor Götz Veser (University of Pittsburgh)</td>
</tr>
<tr>
<td>RAPID’s Process Intensification Principles Webinar Series; series created by Andrzej Stankiewicz and includes webinars by himself as well as Wessel Hengeveld (Flowid), Bob Huss (Eastman Chemical) Adam Harvey (Newcastle University), Joachim Heck (Ehrfeld Microtechnik), and Christophe Gourdon (University of Toulouse)</td>
</tr>
</tbody>
</table>

Webinar Titles:
1. Introduction to PI Principles and Approaches: Structure, Energy, Synergy and Time
2. PI Principles: Structure – PI in the Spatial Domain
<table>
<thead>
<tr>
<th>Topic</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. PI Principles: Structure – Focus on Micro- and Millireactors</td>
<td></td>
</tr>
<tr>
<td>4. PI Principles: Energy – PI in the Thermodynamic Domain</td>
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<tr>
<td>5. PI Principles: Energy – Dynamic Continuous Flow Reactors</td>
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<tr>
<td>6. PI Principles: Synergy – PI in the Functional Domain</td>
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</tr>
<tr>
<td>7. PI Principles: Synergy – Focus on Reactive Distillation</td>
<td></td>
</tr>
<tr>
<td>8. PI Principles: Time – PI in the Temporal Domain</td>
<td></td>
</tr>
<tr>
<td>9. PI Principles: Time – Focus on Oscillatory Baffled Reactors</td>
<td></td>
</tr>
<tr>
<td>10. How to Do Process Intensification</td>
<td></td>
</tr>
</tbody>
</table>

RAPID Webinar: The Value of Process Intensification for Module Manufacturing; 1 Professional Development Hour

2018: 76 registrations Jan-Sep 2019: 76 registrations

Undergraduate students in 3rd or 4th year, graduate students or practicing engineers

Can be found at www.aiche.org/rapideducation
<p>| Speaker: Brian Paul (Oregon State University) | RAPID Webinar: Sustainable Development through Process Intensification; Speaker David Shonnard (Michigan Technological University) | 1 Professional Development Hour | Jan-Sep 2019: 95 registrations | Undergraduate students in 3rd or 4th year, graduate students or practicing engineers | Can be found at <a href="http://www.aiche.org/rapideducation">www.aiche.org/rapideducation</a> |
| RAPID Webinar: Modular Carbon Capture; Speaker Ramanan Krishnamoorti (University of Houston) | 1 Professional Development Hour | Jan-Sep 2019: 98 registrations | Undergraduate students in 3rd or 4th year, graduate students or practicing engineers | Can be found at <a href="http://www.aiche.org/rapideducation">www.aiche.org/rapideducation</a> |
| RAPID Webinar: Modular Chemical Process Intensification: Identifying Opportunities and Overcoming Challenges; Speaker Brian Paul (Oregon State University) | 1 Professional Development Hour | Jan-Sep 2019: 85 registrations | Undergraduate students in 3rd or 4th year, graduate students or practicing engineers | Can be found at <a href="http://www.aiche.org/rapideducation">www.aiche.org/rapideducation</a> |
| RAPID Webinar: Design, Application &amp; Economics of Process Intensification; Speaker Cliff Kowall (Lubrizol) | 1 Professional Development Hour | Jan-Sep 2019: 133 registrations | Undergraduate students in 3rd or 4th year, graduate students or practicing engineers | Can be found at <a href="http://www.aiche.org/rapideducation">www.aiche.org/rapideducation</a> |
| RAPID Webinar: Time-Scale Analysis: A Process Intensification Tool; Speaker Goran Jovanovic (Oregon State University) | 1 Professional Development Hour | 2019: | Undergraduate students in 3rd or 4th year, graduate students or practicing engineers | Can be found at <a href="http://www.aiche.org/rapideducation">www.aiche.org/rapideducation</a> |</p>
<table>
<thead>
<tr>
<th>RAPID and CCPS Webinar: The Link Between Process Safety and Process Intensification</th>
<th>1 Professional Development Hour</th>
<th>2019: 215 registrations</th>
<th>Undergraduate students in 3rd or 4th year, graduate students or practicing engineers</th>
<th>Can be found at <a href="http://www.aiche.org/rapideducation">www.aiche.org/rapideducation</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>RAPID Face-to-Face Course: Modular Chemical Process Intensification Boot Camp; Developed by Brian Paul and Goran Jovanovic (Oregon State University)</td>
<td>32 Professional Development Hours over 4 days</td>
<td>2019: 25 students</td>
<td>Graduate Students and Practicing Engineers</td>
<td>Face-to-face course with lecture, lab exercises, facility tour of manufacturing processes, and project-based exercises. More information can be found at <a href="http://www.aiche.org/ch375">www.aiche.org/ch375</a></td>
</tr>
<tr>
<td>RAPID Face-to-Face Course: Emerging Membrane Processes for Water Purification; Developed by Andrea Achilli, Itzel Marquez and Eduardo Saez (University of Arizona)</td>
<td>34 Professional Development Hours over 4 days</td>
<td>2020: 12 students</td>
<td>Graduate Students and Practicing Engineers</td>
<td>Face-to-face lab and project-based course where students experiment, model and test three membrane processes and scale from bench to pilot-scale. More information can be found at <a href="http://www.aiche.org/ch376">www.aiche.org/ch376</a></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td>In addition to the online webinars and eLearning courses listed above that university faculty can assign to their students, RAPID has developed three design problems/exercises available to faculty:</td>
<td></td>
</tr>
</tbody>
</table>
- Design Problem: Distributed Ammonia Synthesis
- Homework Problem: Dividing Wall Column (includes PPT slides, modelling software and manual)
- Group Exercise: Syngas Production (includes PPT slides and excel sheet for student use)

If interested in obtaining access to these problems for your own classroom use:
www.aiche.org/rapidteachingresources.
<table>
<thead>
<tr>
<th>Course name Instructor(s)</th>
<th>Credits / Level</th>
<th>Editions / # students</th>
<th>Position in the degree</th>
<th>Resources used</th>
</tr>
</thead>
</table>
| J.M. Commenge            | 4 MSc           | Course active for 20 years  
From 20 to 35 students every year | Last year, Semester 1 | Lectures dedicated to (i) an introduction to PI with an overview of most common technologies and principles, (ii) a focus on (micro-)structured reactors for various applications: mixing, control of exothermal reactors, operation in the explosive regime, distributed production, etc.  
Tutorial classes dedicated to (i) design of compact heat exchangers, (ii) reverse engineering of a pilot-scale production unit of ionic liquids, and (iii) a PBL session dedicated to the well-known success story of Merck on a Grignard reaction in 1997. |

Other
This course is coupled to a tutored project dedicated to process innovation: groups of students are exclusively tutored by industrial engineers and work, during four months, on an open problem dedicated to the conception and design (or debottlenecking and retrofit) of a process related to energy production and/or transformation.
<table>
<thead>
<tr>
<th>Course name</th>
<th>Instructor(s)</th>
<th>Credits / Level</th>
<th>Editions / # students</th>
<th>Position in the degree</th>
<th>Resources used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Intensification</td>
<td>Kamelia Boodhoo, Adam Harvey, Richard Law, Jonathan Lee, Vladimir Zivkovic</td>
<td>5 ECTS MEng/ MSc</td>
<td>2015-2016/70 2016-17/71 2017-18/67 2018-19/75 2019-20/90</td>
<td>4th year MEng in Chemical Engineering students (UG)/1st year MSc in Sustainable Chemical Engineering (PG), Semester 1</td>
<td>Students get 2 lectures and 1 tutorial on each technology as a minimum. In total, students have about 12 hours of lectures and 6 tutorial hours where they practise solving problems relating to design of the technology. Students are provided with additional reading material such as research articles, text-books which they are meant to consult/review in their independent study time to supplement basic knowledge provided in lectures.</td>
</tr>
</tbody>
</table>

Other Students are taught by academics who are experts on a specific PI technology. The technologies covered are spinning disc reactor, oscillatory flow reactor, compact heat exchangers, rotating packed bed and microreactors.

For their in-course assessment, each student is asked to write a technology briefing on a PI technology of interest (other than the ones they have studied in the course) based on available literature sources. This helps to broaden their awareness of a wider range of PI technologies and develop the skills to evaluate the intensification potential of the technology in relevant applications.

Intended knowledge outcomes of the course:

1. To understand the concept of Process Intensification and the methodologies for PI
2. To appreciate the benefits of PI in the process industries
3. To understand the operating principles of a number of intensified technologies such as the spinning disc reactor, the rotating packed bed, the oscillatory flow reactor, compact heat exchangers, and microreactors.
reactor, the compact heat exchanger and the catalytic plate reactor. To appreciate the range of potential applications of the above-mentioned intensified equipment.

Intended skill outcomes of the course:

1. To design equipment capable of intensifying conventional processes. 2. Problem Solving skills.

See Example 1 in Y4 for how the skill developed in this module can be applied in a problem-based learning environment.

TRIZ activity at HS Offenburg in Germany (Law et al., 2017; Livotov, 2019; Livotov et al., 2019; Livotov and Petrov, 2013) Livotov led the work on TRIZ in the HORIZON 2020 project – Intensified by Design (IbD). Very successful in brainstorming improvements to existing PI plant and identifying patentable areas and new concepts, via workshops. See the 4th paper in comment for examples.
Appendix 2. Cognitive Processes Description

Remember. According to (Anderson and Krathwohl, 2001), remember means to “retrieve relevant knowledge from long-term memory” either to recognize or identify something known or simply to recall a fact or any other information (p.66) (Anderson and Krathwohl, 2001).

Understand. Understanding knowledge exceeds rote learning. When students understand a concept, they are constructing a personal meaning for it. When an instructor demonstrates in front of them how to solve a problem or analyse a situation, students internalize how to solve a problem or how to analyse a situation. They try to «understand» passively how they should proceed without necessarily being able to do it by themselves. Thereby, teaching and learning activities should not be limited to demonstrations but should also include a sequence where students are actively tackling the task by themselves and the educator is there to help them apply the algorithm or analyse the problem. Moreover, students understand when they are connecting new knowledge to their prior knowledge. What if they don’t have any prior knowledge about what is taught? Finding an analogy to which new knowledge can be connected is a solution. Beginning the class with an experiment or a demonstration to which new knowledge is directly related, is another way to maximize students understanding.

Apply involves the use of a procedure to solve a problem. There are two levels of application. When the students are familiar with the task, they know what procedure they have to follow; but when the task is not familiar, students have to choose among different steps to take according to the context. This later context involves the ability to execute, a profound comprehension of the situation and the options (steps) available.

Analyse involves separating a concept into its components and observe how the components are related to one another. It also involves separating a situation into its parts and observing how they are functioning as a system. To analyse a situation means to pair the situation components with concept attributes to observe how conceptual knowledge can enlighten the real-life situation.

Evaluate involves the students being able to produce a judgment often based on standards and criteria shared by experts of a scientific domain. Students are able to detect fallacies or inconsistencies. They can expose and defend how they came to their critical judgment. It presupposes an analysis followed by the statement of a professional judgment.

Create. Creativity involves putting elements together to form a new coherent whole. All the previous cognitive processes imply working with a given set of elements. But creativity involves putting elements from numerous sources together to create a new solution. “The creative process can be declined into three phases: problem representation, in which a student attempts to understand the task and generate possible solutions; solution planning, in which a student examines the possibilities and devises a workable plan; and solution execution, in which a student successfully carries out the plan.” (Anderson & Krathwohl, p.85 (Anderson and Krathwohl, 2001))

The relationship between the cognitive processes
These cognitive processes are interdependent. Students cannot be creative if they haven’t first developed analytical thinking skills, as well as if they cannot make the link between scientific concepts to the components of a real technical application, e.g. a heat exchanger plug flow reactor. This means that teaching and learning activities that make the students successfully creative inevitably mobilize the previous cognitive processes. What can we do when students do not succeed? We can offer them resources to help them master previous cognitive processes. When a student or a team is unable to analyse, it means that they do not master the concepts required for that specific analysis. Therefore, we need to invite them to go one step backward and relate the components of a concept to a real application.
Appendix 3.0. Lower order cognitive level – Bloom’s example: Thermodynamics of Process Intensification

Here we show that reduced heat and mass transfer resistances, which PI targets, lead to processes that are more energy efficient. When mechanical processes operate at a higher throughput, they often become less energy efficient owing to the dependence of mechanical losses (e.g., friction, drag and other viscous forces) on velocity. Similarly, with chemical processes, achieving higher reaction rates by imposing high temperatures and pressures (as opposed to using a catalyst under less extreme conditions), incur in inefficiencies owing to mechanical losses, other parasitic losses of energy to the environment, and decreases reaction selectivity associated with finite rates of transport of mass or energy (e.g. hotspots).

The loss in energy efficiency arises because of the generation of entropy, $S_{irr}$, that triggers the irreversibility of spontaneous processes:

$$dS_{irr} = dS + dS_e > 0$$

where, following Denbigh (Denbigh, 1951), $dS_{irr}$ is the sum of the entropy change in the system, $dS$, and that of its environment, $dS_e$. In the case of a process operating isothermally at steady state where only heat, $dQ$, is exchanged between the system (at a temperature $T$) and its environment (at a temperature $T_e$), the entropy flow into the system and from the environment are $dS = dQ/T$ and $dS_e = dQ/T_e$, respectively, thus the sum of the entropy flows is:

$$dS = \frac{dQ}{T} - \frac{dQ}{T_e} = dQ \left(\frac{1}{T} - \frac{1}{T_e}\right) = dQ \frac{T_e - T}{T \ T_e} = -dQ \frac{dT}{T^2}$$

when the difference in temperatures is small. The rate at which heat can be moved between the environment and the system is proportional to the effective heat transfer coefficient, the contacting area and the temperature difference. The effective heat transfer coefficients of intensified process equipment can be 100-1000 times larger than in conventional equipment (Reay, 1991). Thus, the temperature gradient, $\Delta T$, is proportionately smaller to transfer the same quantity of heat, leading to more reversible, and thus more efficient processes (smaller $dS_{irr}$).

Contrarily, an optimal fluid mixer maximizes entropy using as little work as possible. Of course, mixing is spontaneous so, in principle, no work needs to be added to accomplish it. However, to achieve the mixing rapidly does require inputting energy to afford the division and intermixing of the fluid elements. To estimate the energy required to achieve maximum entropy, consider an adiabatic system in which the work input, $w$, is completely degraded into thermal energy, $q$, raising the system to a temperature, $T$. In that case, from the conservation of energy, $dq = dw$, and the increase in irreversible entropy in the system is:

$$dS_{irr} = \frac{dq}{T} = \frac{dw}{T}$$

For the simple case of mixing equal amounts of two pure components, A and B, which form an ideal solution, the generated, irreversible entropy is:

$$dS_{irr} = -R[x_A \ln(x_A) + x_B \ln(x_B)]$$

In the resulting mixture, the mole fractions of both $x_A$ and $x_B$ is 0.5 so, the work that could be done by the mixing (e.g., in a concentration cell), at say, 300 K, is:

$$dw = TdS_{irr} = -RT(0.5 \ln(0.5) + 0.5 \ln(0.5)) = 1.73 \text{ kJ/mol}$$
To illustrate the magnitude of power equivalent to that degree of mixing, assume the molecular weight of each component to be 100 g/mol and that the mixing time (residence time in the mixer) is 100 s:

\[ P_{\text{mix}} = \frac{1.73 \text{ kJ/mol}}{0.100 \frac{\text{kg}}{\text{mol}} \times 100 \text{ s}} = 173 \text{ W/kg} \]

which is in the range of modern, static mixers (Stankiewicz and Moulijn, 2002) and about two orders of magnitude higher than that of a conventional, stirred tank. When additional input power, \( P_h \), only compensates for pressure heads, and does not contribute to the mixing, it lowers the efficiency of mixing, \( \eta_{\text{mix}} = P_{\text{mix}}/(P_{\text{mix}} + P_h) \).

A more general and more precise analysis is related to “Finite-Time Thermodynamics” (FTT (Andersen, 2011)). Real engineering processes have to run to a reasonable degree of completion within a finite period of time and optimizing the operating conditions depends on the target (objective function) to be optimized (maximum power production, minimizing entropy production etc.). In reversible thermodynamics, all the objective functions are optimal at the same time, because, when the process is reversible, there are no losses and all the objective functions are equally important. An essential concept introduced by FTT is the thermodynamic length. The thermodynamic length (Crooks, 2007) is the distance between two equilibrium thermodynamic states. The starting point for calculating a thermodynamic metric is always the full equation of state for the system in question. Applications of this approach to distillation and chemical reaction are presented by Andersen (Andersen, 2011). Durmayaz et al (Durmayaz, 2004) reviewed the optimization studies of thermal systems, which consider various objective functions, based on FTT, as well as thermoeconomics. The same paper also reports some objections to the FTT method.

Kingston and Razzitte (Kingston and Razzitte, 2017) report entropy production in continuous stirred tank reactors and plug flow reactors. Torabi et al. (Torabi et al., 2019) present a special issue of the journal “Entropy” of the non-equilibrium analysis of micro devices, like micro reactors, micro-scale thermoelectric coolers etc. Although not specifically related to PI, Rosjorde et al. present (ROSJORDE et al., 2007) an example of minimizing entropy production in a process for dehydrogenation of propane. In a rather comprehensive paper Leites et al. (Leites et al., 2003) have examined the causes of thermodynamic irreversibility in chemical reactions and other industrial chemical processes (in particular absorption, stripping, and heat transfer).
Appendix 3.1 Higher order cognitive level – Bloom’s example: Comparing two devices

Based on an example from Reay’s book Chapter 5, pp 159-160 (Reay et al., 2013), the students analyse the differences between two devices, one conventional, and one intensified (Oscillatory Baffle Reactor, OBR).

Oscillatory baffle reactor (OBR)

Conversion of a batch saponification reaction to continuous processing in an OBR to result in a 100-fold reduction in reactor size, as well as greater operational control and flexibility.

By looking at a set of parameters or data corresponding to each reactor, the students evaluate the advantages and disadvantages of each option. To assist in the evaluation, a simple method is used to provide a numerical value defined as Intensification Factor (IF) (Reay et al., 2013). There can be different processes, units or independent equipment (such as the batch reactor replaced by the OBR) needing intensification or improvement. A given factor (F) can be the operation time, the yield of a given reaction, or the residence time. For a given factor F, we have as input data its initial value Fb, the value after the modifications Fa. An exponent d will serve in two ways: first, the sign will be determined whether a decrease or increase in F is beneficial; second, its absolute value will be taken as a weight factor that will depend on its importance with respect to the final goals of the intensification strategy.

\[ IF = \left( \frac{F_a}{F_b} \right)^d \]

The meaning of the absolute value of d needs to be determined by specific intensification targets; e.g. safety, cost, environmental impact; and would typically be set by experts. If such information is not available or agreed by experts, it can be set to unity. For simplicity, the absolute value of d is taken as 1 for our course, and we have:
It follows that intensification factor for a given number of n changes is calculated as:

\[
d(F) = \begin{cases} 
+1 & \text{if a decrease in } F \text{ factor is desired} \\
-1 & \text{if a decrease in } F \text{ factor is undesired}
\end{cases}
\]

\[
IF = \prod_{i=1}^{n} \left( \frac{F_{bi}}{F_{ui}} \right)^{d_i}
\]

The factors used for the IF calculation of this test-case are Temperature, Pressure, Volume and Residence time. The students then build a table that allows them to calculate the individual IF values, and the total is presented as follows:

<table>
<thead>
<tr>
<th>Factor</th>
<th>Batch</th>
<th>OBR</th>
<th>d</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature [K]</td>
<td>115</td>
<td>85</td>
<td>1</td>
<td>( \left( \frac{115}{85} \right)^{1} = 1.35 )</td>
</tr>
<tr>
<td>Pressure [bar]</td>
<td>1</td>
<td>1.7</td>
<td>1</td>
<td>( \left( \frac{1}{1.7} \right)^{1} = 0.58 )</td>
</tr>
<tr>
<td>Volume [m³]</td>
<td>75</td>
<td>0.5</td>
<td>1</td>
<td>( \left( \frac{75}{0.5} \right)^{1} = 150 )</td>
</tr>
<tr>
<td>Residence time [min]</td>
<td>120</td>
<td>12</td>
<td>1</td>
<td>( \left( \frac{120}{12} \right)^{1} = 10 )</td>
</tr>
</tbody>
</table>

\[IF_{total} = 1.2E3\]

For this case where a decrease in Temperature is desired, the d value is taken as positive. It is assumed that a decrease in pressure is desired due to safety and costs, that is why the IF\textsubscript{pressure} is less than one, decreasing the IF\textsubscript{total} value. Interestingly, a new IF number could be calculated to assess what happens at a higher pressure (d = −1), for example when the reaction kinetics are favoured. In contrast, for Volume and Residence time the d value is 1, because is better to work with less inventories. The final IF is 19.44>1 meaning that the new proposed reactor has an overall positive performance. See Appendix 6.2 for more detail.
Appendix 3.2. Example of Problem-based learning (PBL) in the course Process Intensification Principles in the University of Twente (1).

Example of Problem-based learning (PBL) or Challenge Based Learning (CBL), whereby two groups are given the same problem, but asked to use different technologies each with competing advantages and drawbacks.

**Process Intensification Assignments**

*Instructor: David Fernandez-Izquierdo, Meso-scale Chemical Systems, Course 2016-2017*

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**General topic**

Water treatment and cleaning surfaces

There are several techniques used in chemical engineering for the conditioning of water, as well as cleaning water pipelines and containers. Water is found in nature, or after human activities, having several properties that might make it impossible to use, for example for animal or human consumption.

One of the oldest means to prepare water for its consumption is boiling, or addition of iodine salts that can reduce the presence of microorganisms and degrade dissolved undesired compounds. But the ultimate goal is the complete mineralization of pollutants to environmentally harmless compounds.

When pipelines are used for too long, there are probabilities that bacteria starts forming biofilms that stick to the walls, which has a negative influence on health and operation of the water supply systems.

In these series of assignments we cover different hypothetical scenarios in which the treatment of water is required either for a chemical process, special uses in medicine, or just the reduction of contamination footprint.

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The following is expected from the groups:

- Work in teams and evidence professional skills simulating real-life scenarios.
- To design a solution, formulate and combine knowledge based on the assignment-scenarios given.
- Defending and backing the propositions and views based on literature and industrial examples.
- Compete professionally against the opposing assignment team towards finding an optimal solution to the problem.

**Time plan:**

- Assembling of groups and distributing the assignments: First Meeting, September 8th, 2016.
- Proposal
  - Submission: Meeting 7 (October 20th)
  - Peer reviewing of Proposal (300 words) Turnitin (from Submission)
- Poster submission: Ongoing meeting
- Poster presentation: 2nd meeting.
- Executive reports: Ongoing meeting.
- Three pages: Two with text (word limit: 660), and one for figures and schemes.
- Presentation: Weeks 02, 9 and 10
  - 15 min presentation, 10 min questions (2 team members present and a answer questions).
**Format and Documents**

- A Photograph of the team with the names of each on a paper in front of them.
- Abstract:
  - Title, name of group members, word document (250 words) explaining the conceptual design.
- Poster presentation:
  - PowerPoint or PDF format. It will be printed in normal A4 pages.
  - On the day of the Poster session there will be stands available for presenting it to the other class participants.
- Executive report:
  - Three pages. Two with text (word limit: 700), and two for figures and schemes. Figure captions and references don't count against page or word limits.
  - Summary (short paragraph 150 words limit)
  - Process info and background
  - Equipment design and Individual Tasks performed within the team.
  - Determination Factor calculation and considerations, Safety, Economical, Environmental, Technical, etc.
  - Discussion and Conclusions.
- Naming files: 2016/Proj_Gxx.XXX
  - 2016_P4_30a_PosterVersion.ppt (Poster Final version one of Group 2).
  - 2016_P4_30a_ExeReportFinal.doc (Executive report final version of Group 16).

**Assignments 4A and 4B**

- ULTRASONIC BATH
- ULTRASONIC HORN

The University of Twente has detected in the past the presence of *Legionella* in the sport center. Also, *P. aeruginosa* and *E. coli* are one of the most challenging bacteria to kill, and have a negative impact on human health. The students are tasked to find a technical solution for the removal of this sort of contamination from the water pipes in Campus. A demonstrator device is needed to test the different possibilities that will be contracted in the next future (6 months) from a research-manufacturing consortium.

It is known that these types of microorganisms generally grow in biofilms, hence special attention needs to be given to the prevention and removal from the inner surface of water pipes and other containers. It is desired to avoid the use of chelating or other chlorine solutions.

**Find a technical solution for the use of an ultrasonic bath**
- Cavitation reactor.
- Combination with UV radiation should be considered as a strong candidate to intensify the removal efficiency.
- The balance in present hydrophobic and hydrophobic compounds dissolved in the water needs to be considered.

**Provide a design of combined techniques including the use of an ultrasonic horn.**
- Combination with Monocoal technology could be an interesting direction to go.
- Keep in mind the temperature effects and how they could influence the optimal performance of the final device.
Appendix 3.3 – Example of Problem-based learning (PBL) in the course Process Intensification Principles in the University of Twente (2).

The PBL activity consists in assembling first a group of students (mixed by the results of Belbin’s test and background). The groups can choose among three (3) case studies. Each group-leader submits a list with the case studies in order of preference. The professors assign the case studies to each group with no more than four groups working on each case. Each group is also assigned a specific context to facilitate discussion about the ecological or societal impact of the intensified process. They later use the IF method (Appendix 3.1), and feed values calculated with AspenPlus Software. The instructor serves as tutor or advisor at all stages in the project.

Case studies
Reactive Distillation
This case comprises the modelling and optimization of the process that produces Dimethyl ether (DME). DME is widely used in industry as a clean fuel for diesel engines or in combustion cells. DME is produced by the conversion of feedstock such as natural gas, coal, oil residues, but also from bio-mass into syngas, which is a renewable energy source. The first step involves the conversion of syngas to methanol over a Cu catalyst, and then its dehydration over γ-alumina or zeolites to produce DME. The traditional industrial process includes a fixed-bed reactor, followed by two distillation columns delivering high-purity DME (>99.99 %). Reactive distillation can replace the reactor and the two-distillation column with one unit.

Vapor recompression
This case comprises the modelling and optimization of the separation of a propane/propane mixture, which is one of the most important processes in petrochemical industry. This separation poses great challenges due to the similarity of both molecules and the close boiling points. At atmospheric pressures, cryogenic distillation is used to separate the mixture, however it is also possible to perform this distillation at elevated pressures. A typical distillation column for the separation of the mixture at high pressure requires around 250 stages and very high reflux ratios are needed. This combination makes the system very capital expensive, and energy intensive. Many other separation techniques for the separation of this mixture are researched by researchers around the world, but the system can also be intensified with novel techniques within the field of distillation. Since the boiling points of both components are close, vapor recompression can be utilized. Heat integration of a distillation column is only possible when the top product stream condenses at a higher temperature than the bottom product stream. With this technique, the top product stream, without utilizing the condenser, is pressurized which will increase the temperature of this stream, which enables heat integration of the column.

Dividing Wall Column
Mixtures of aliphatic alcohols can be produced from synthesis gas by the partial oxidation of methane or naphtha. These alcohols are valuable, since they can be used in internal combustion engines or to synthesize methyl- and ethyl ethers with high octane numbers. This case study involves the separation of a mixture of three components: ethanol, 1-propanol and 1-butanol. Two distillation columns usually separate the three components. In the first column, the ethanol separates from the 1-propanol and 1-butanol. In the second column, the 1-propanol separates from the 1-butanol. A divided wall column can intensify the process. A
divided wall column is a distillation column that can separate three components in a single column with the addition of a vertical wall in the middle of the column. The feed will be injected on one side of the column and the reflux and re-boil streams are divided between the two sides of the column. By doing this, the component with the middle boiling point can be collected with high purity.

**Context for each case**

<table>
<thead>
<tr>
<th>Context a</th>
<th>Context b</th>
<th>Context c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management can be hard to be made aware on the ecological impact of the company’s operations. Your plant is located in the following map.</td>
<td>Government subsidises the use of alternative sources of energy. Your plant is located in the following map.</td>
<td>Strong social pressure to relocate the plant, but is not possible to do so. Your plant is located in the following map.</td>
</tr>
</tbody>
</table>

![Maps](https://example.com/maps.png)
Appendix 3.4 – Examples of Challenge-based learning (CBL) at Newcastle University

Example 1. Final year undergraduate students on the 4-Year Master of Engineering (M.Eng.) Programme undertake an individual research project over a 3 months period, applying and evaluating a specific PI approach to a process of interest in the PI group. They develop skills in designing the experimental methodology to gather data for analysis and interpretation. In the recent years, students have undertaken research projects related to spinning disc reactors, oscillatory flow reactors, microreactors and rotating packed beds, which gives them hands-on experience of these technologies and their application to processes of industrial relevance. Every year, about 30 students carry out a research project at the PI group at Newcastle. Often, peer-reviewed conference or journal papers result from such projects.

Example 2. In some third-year design projects, students carry out a design exercise based on intensified systems for a given target product and production objective. One recent example involved the design of a spinning disc reactor to produce a bio-based polyester from hemicellulose waste streams. The student was able to synthesise new knowledge and create a new polymer reactor design for this novel application. The final outcome was a multi-disk design to increase conversion in the final stage of the polymerization process.
Appendix 3.5. Applying techno-economic formulas of factor analysis to commercialize PI technologies (different from commercializing traditional technologies).

Following the four (4) key PI principles: i) Maximize the effectiveness of intra- and intermolecular events; ii) Give each molecule the same processing experience; iii) Optimize the driving forces at every scale and maximize the specific surface area to which these forces apply; iv) Maximize the synergistic effects from partial processes (Van Gerven and Stankiewicz, 2009), it is evident that these principles are more easily achievable at smaller scales. Selecting geometry and typical unit dimensions becomes therefore key to design intensified systems. Modular units then become the tool to achieve economies of scale by the “numbering-up” (Patience and Boffito, 2020; Weber and Snowden-Swan, 2019).

This is why there is the need of new, established investment models that break up from the traditional ones, which only apply to classic unit operation equipment, e.g. Chilton’s six tenth rule (Tribe and Alpine, 1986). Some of these models are based on the concept of experience, whose original theory relies on the observation that labour costs decreases when workers repeat routine tasks (learning). (Wright, 1936) These models can be applied to conduct sensitivity analysis in the context of PBL or CBL to develop higher order cognitive skills on process design (Table 1). The amount of experience gained with an increase in the cumulative production is best expressed by “Experience curves”, which are plots of the log(cumulative production, \( Q \)) vs. the log(price \( P \)).

The students can employ empirical experience curves (i.e. \( P = k(\sum Q)^\beta \)). Where the slope of the curve, \( \beta \), is the mean learning elasticity (Lieberman, 1989). \( \beta = 1-1/n \) and \( \alpha = 1/(1-n) \), where \( \alpha \) is the Chilton’s scale factor and \( n \) is the typical unit scaling dimension (i.e. \( i=1 \) for pipes, \( n=2 \) for units that scale by surface area, \( n=3 \) for reactors, etc.).
Appendix 3.6 Example of Challenge-based learning (CBL) at Utrecht University of Applied Sciences

One of the courses offered in the third year of the Chemical-Engineering B.Sc. programme is the Project “Process Optimisation”. During this course, a group of three to four students works on a problem proposed by an industrial partner. The students spend approximately 22 weeks working on this problem (part-time) and are expected to work on-site at the company for one day per week. Students generally enjoy this course despite its complex subject, because they perceive the real impact their data can generate and they get to interact with (and are supervised by) industry professionals.

While this project is not necessarily focused on PI, there have been several instances over the past years in which describing the benefits and drawbacks of using PI technology was its primary goal. Past experience with a certain type of PI reactor technology allowed our lecturers to reach out to industrial partners and give them an impression of its potential benefits. This led to various companies expressing their interest in having a group of students investigate the possible benefits for their specific process. In several cases, this course has subsequently resulted in the company deciding to start using the PI technology.

During the course, the students are supervised both by an internal supervisor (a lecturer at the University) and an external one (an employee at the company), both of whom play a significant role in the assessment. The course allows for evaluation of some of the higher-level cognitive skills, such as evaluate and analyse. Transferable skills such as teamwork, critical mindset, information management, communication and creativity can be trained and evaluated, as well as technological aspects. To avoid evaluating each skill for every student, the assessment was recently redeveloped to allow students to choose which soft skills they would focus on, and to coach them in this process. In addition, the choice was made to focus the evaluation on the interests of the stakeholders (e.g. why is this technology beneficial for this company? What would be potential pitfalls? What about cost and benefit?) rather than purely on technological aspects.
Appendix 3.7 Example of Challenge-based learning (CBL) at Polytechnique Montréal, Department of Chemical Engineering

Polytechnique Montréal has recently modified their Capstone design course to include a 3-credit component dedicated to economic analysis and process selection during the first semester of the final year. In the second semester of the final year, the design course component is worth 6-credits (equivalent of two courses). Each team of 4-6 students requires an industrial partner and so the focus is heavy on innovation to solve their problems and introduce novel designs, which entails process intensification concepts. The subjects vary from extracting metals from electronic waste, depolymerizing and thermochromically activating polymers with microwaves, to developing micro-refineries that operate in remote locations. The process intensification aspects of these projects are tremendous as the students have to develop economic strategies so that these technologies are able to compete with the standard stick-built processes. Furthermore, the program has now introduced mechanical and electrical engineering students to the course to better identify materials of construction for high temperature/high pressure vessels and control strategies and instrumentation. Integrating the 3-credit economics component to the design course has been extremely successful: in the last four-years, students from Polytechnique have placed in the top 3 positions in the nationwide Hatch competition that is held at the annual Canadian Society of Chemical Engineering Conference.

Appendix 3.8 – Case Study for the students in the Energy MSc and Chemical Engineering at Heriot-Watt University, Edinburgh, also called BHR Group methodology. Circa 2012.

Example of Challenge-based learning (CBL)

This method applies exclusively to innovation by PI and during process development of an existing process to replace or upgrade. It consists of a number of protocols detailing the information needed to ensure that the potential for PI is quantified with the highest accuracy as possible. The methodological steps are:

1. Overview the whole process;
2. Examine the chemistry and the unit operations;
3. Identify business and process drivers;
4. Identify rate-limiting steps;
5. Generate design concepts;
6. Analyse the design concepts;
7. Select the equipment;
8. Compare the PI solution(s) with conventional equipment;
9. Make the final choice.

The order of these may vary, and some activities are continuous throughout the project. More detail can be found in the Chapter 12 of the book and its appendices. We report hereinafter some data from the case study: “Monoethanolamine (MEA) Production” (Chapter 12).

1. Overview of the whole process: The process is reviewed from a general point of view such as ---
2. Examine the chemistry and the unit operations: By first drawing the process flow diagram (PFD) (Figure A3.8.1), each unit is identified along with its operating conditions, typical reagents ratios, yields and selectivity. Characteristic reactions, both desired and undesired, are then listed together with the reaction enthalpy and heats
of formation of each product. At this point, it is recommended to identify strongly exothermic or endothermic reactions.

![Figure A3.8.1 Typical flow scheme of mono-, di- and triethanolamine (MEA, DEA and TEA) using ethylene oxide and ammonia injection, from (Reay et al., 2013).](image)

3. Identify business and process drivers: This should also include a PESTLE (Political, Economic, Social, Technological, Environmental). We do not enter in the detail of this analysis, but we invite the readers to refer to the book for more detail. However, in a few words, these drivers coincide with the general drivers to intensify processes and have to do with the wish of developing greener, more carbon efficient technologies. For MEA production, business drivers to intensify the process demand to reduce energy requirements and plant size, with the possibility of adopting micro-plants. As a consequence, maintenance and operating costs (M&O) would decrease along. The cost for the new project development may likely increase. Process drivers demand higher yield of MEA, which also benefits the business case. Higher production rates of MEA may as well decrease is sale price and make it more competitive in a scenario whereby its demand will raise as post-combustion carbon capture systems become more common.

4. Identify rate-limiting steps: The primary (and desired) reaction is highly exothermic and requires efficient cooling to maintain the optimum reaction temperature. The traditional system involves pressures up to 160 bar, which may be lowered slightly but will need to remain well above ambient to maintain ethylene oxide in the liquid phase. If ethylene oxide molecules do not have sufficient access to free ammonia molecules, they will react with higher substituted amines, forming the mostly undesired DEA and TEA.

5. Generate design concepts: 5a) The amine heat exchanger could be intensified, it could be integrated to supply some heat to the feed streams for the reactor or to some of the downstream separations such as the water evaporator; 5b) The last three columns are traditionally plated distillation columns which could quite easily be switched for the rotating distillation column that would provide the same efficiency, increase safeness and reduce size, environmental impact and capital costs; 5c) Compact heat exchangers (CHEs) could be used in the reboilers and condensers on separation units to give greater control of heat flows and recovery can increase the economic and thermal efficiency of these operations; 5d) Several options are available to intensify the reactor: an oscillatory baffled reactor (OBR), a spinning disc reactor (SDR), and a rotating packed bed reactor (RPB).
6. Analyse the design concepts: Chapter 12 of (Reay et al., 2013), identifies all the pros and cons of the three intensified reactors, including downstream operations. For sake of brevity, we invite the reader to consult the book for further detail.

7. Select the equipment: to select equipment it is best to draw a process flow diagram (PFD) of the all the intensified solutions under analyses, in this case: i) a SDR with aqueous ammonia and CHEs; ii) a RPB with gaseous ammonia and similar downstream equipment to the SDR; iii) a RPB in place of the SDR with zeolite catalysis to enhance yield but with one more rotating distillation column to separate liquid NH₃.

8. Compare the PI solution(s) with conventional equipment: All solutions follow a similar configuration as the traditional process flow, but the final column has been eliminated and the other operations have been intensified. The tubular reactor has been replaced with either an SDR or RPB and the columns have been switched from plate distillation to rotating distillation columns. Also, there is a CHE system that pre-heats the ammonia feed using the heat from the DEA and TEA residue streams out of the final column and there is a similar system for the ethylene oxide where heat is recovered from the ammonia and water recovery line, and from the SDR or RPB to enhance plant efficiency and to reduce inherent associated emissions through heat sourcing. All the three solutions, while very similar to the first one on paper, will be vastly smaller than the former due to the size reductions achievable using these units. They will have a much smaller visual physical and chemical impact on the environment and will be much simpler to operate to a high safety standard as well as being easier to clean and maintain.

9. Make the final choice: The best process to go for in terms of size, output, capital and operational cost and overall environmental and visual impact is solution ii), i.e. the RPB with gaseous ammonia feed. It eliminates the need for a dedicated ammonia separation system and only has three large operations in place with some additional compression and heat exchange (Figure A3.8.2) This configuration also eliminates the need for huge volumes of water, which reduces capital cost reduction. Using gaseous ammonia in a pressurised system does present significant safety risks but the system is designed to be as low inventory as possible at every operation in a bid to mitigate these risks.
Figure A3.8.2 Intensified monoethanolamine (MEA) production using gaseous ammonia and liquid ethylene oxide in an RPB reactor, rotating distillation columns and integrated heat systems for capital and energy efficient processing, from (Reay et al., 2013).
Appendix 3.9 Example of introducing microreactor technology in the first year practical course at Eindhoven University of Technology (Noel, 2019).

The “Practical Introduction Course to Chemistry and Chemical Technology” is the first practical course for the first year BSc students (about 120 students/year) at the department of Chemical Engineering and Chemistry. The course aims to teach the students the required practical skills to work safely in a chemical laboratory. Within the course, the students learn how to execute chemical recipes accurately (both analytical chemistry and synthetic work). A large part of the course is also focused on some basic chemical engineering experiments. This includes black box experiments where students need to predict based on residence time distributions which reactor is inside the black box (CSTR or PFR), reaction kinetics and mass balances, reaction heat and enthalpy experiments, and determination of the reaction rate constants of simple transformations.

However, in 2015, we introduced also microreactor technology to the course. The students assemble their own flow setup using polymeric capillaries and commercially available and reusable microfluidic fittings. We believe that despite the simple design of the reactors, there is a genuine pedagogic value in designing your own flow reactors. The students love the Lego-type assembly of the reactors and they also generate ideas for further improvement of the design.

Two different flow experiments are carried out in the lab in teams of two students. As a first experiment, they make diazodyes in a two-step fashion. The intermediate is a diazonium salt, which is potentially explosive. The experiment is an example where hazardous compounds can be generated and be reacted away immediately in a follow up reaction. Hence, the risks associated with this potentially explosive substance is efficiently minimized (Kockmann et al., 2017). The students measure subsequently the progress of the reaction with UV-VIS spectroscopy and they have to determine the reaction rate constant. Using the reaction rate constant, they subsequently estimate the time it requires to reach 99% conversion. As a second experiment, they carry out a two-phase organic-aqueous reaction in a microreactor to enable the dimerization of octanethiol to the corresponding disulfide using hydrogen peroxide. This shows the famous segmented flow regime and the students have to isolate the final product in the end.

Our aim is to show the students that there is a viable alternative for the classical round-bottom flask. The two examples were chosen to demonstrate some key advantages of microreactor technology and flow chemistry, e.g. multistep reaction sequences, handling of hazardous reagents, and multiphase reaction conditions. Overall, the students really like the microreactor technology part and this feeling has been consistent in the past five years. Our experience also shows that flow chemistry does not necessarily have to be expensive to implement in the curriculum. The main cost is associated with the initial investment to purchase the syringe pumps. However, as these pumps can be used every year and never got damaged so far, the overall cost can be neglected.

Finally, we firmly believe that this type of experiments should also be amenable to chemistry curricula and should not be reserved to chemical engineering disciplines. If process intensification wants to really break through, we have to get everybody on board and show all disciplines that it has value for their respective fields. Moreover, as such, we provide students with the broadest possible experience and they can then further decide in their professional careers whether or not to implement process intensification.
**Appendix 3.10.** How to design a sustainable, inherently safer processing plant (used in TU Delft and KU Leuven).

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**Course Information per Year**

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**Course Items**

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<td>A. J. Steinkeiwicz</td>
<td><a href="mailto:a.j.steinkeiwicz@tudelft.nl">a.j.steinkeiwicz@tudelft.nl</a></td>
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**Contact Hours / Week**

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**Education Period**

3

**Start Education**

3

**Exam Period**

4

**Course Language**

English

**Expected prior knowledge**

Basic chemical & process engineering (e.g., BS Chemical Technology course); heat and mass transfer

**Course Contents**

1. Introduction to Process Intensification (PI):
   - sustainability-related issues in process industry;
   - definitions of Process Intensification;
   - fundamental principles and approaches of PI.

2. How to design a sustainable, inherently safer processing plant:
   - presentation of PI case study assignments.

3. PI Approaches:
   - STRUCTURE - PI approach in spatial domain (incl. "FOCUS ON" guest lecture)
   - ENERGY - PI approach in thermodynamic domain (incl. "FOCUS ON" guest lecture)
   - STINERGY - PI approach in functional domain (incl. "FOCUS ON" guest lecture)
   - TIME - PI approach in temporal domain (incl. "FOCUS ON" guest lecture)

The series of lectures in Q3 is followed in Q4 by a case-study project, in which groups of students develop conceptual design of an intensified chemical plant.

**Study Goals**

Upon completion of the course the student will have basic knowledge of process intensification principles, equipment and processing methods, and will be able to apply them to a conceptual design of intensified, inherently safer chemical plants.

**Education Method**

Lectures, case-study project in groups

**Literature and Study Materials**

Basic study material:

1. Lecture handouts


Additional materials will be distributed at the start of the case study project.

**Assessment**

Written examination, report + presentation of the case study project

**Department**

3ME Department Process & Energy

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https://coursebase.tudelft.nl/le64_editCourse.do?showchanges=true&course_id=49526
Appendix 4 List of reasons why PI large-scale equipment and microreactors are not widely used in industry

- Insufficient technical understanding of all the physical/chemical phenomena and their interaction within the process equipment, in particular unavailability of sufficiently well-founded modelling, and, therefore, no sound theoretical basis for reliable scale-up.
- Very complex interaction of reaction, flow, and heat/mass transfer, particularly when alternative energy sources (e.g. ultrasound, microwaves, plasma) are adopted, and/or non-traditional driving forces play a role.
- Poor prediction of how much more development is required to scale-up, due to lack of real experience.
- Equipment standardization is unavailable.
- Certifications are missing: some new devices and manufacturing processes are not part of approved procedures; for example, high-pressure reactors built by metallic additive manufacturing.
- Lack of design software for process design/modelling and PI equipment.
- Lack of basic data, e.g. intrinsic kinetics, transfer capacities, rheology, physical properties at non-conventional conditions (e.g. plasma).
- Lack of chemical process design software that includes PI technology as they tend to include traditional and well-known unit operations and equipment only (previous point).
- Unclear market knowledge (how large is it? What is really needed?); therefore, it seems too risky for many companies to develop PI equipment in advance.
- Insurmountable fouling problems in any process where particulates accumulate over time, or where solids can be formed under certain undesirable conditions (e.g. ortho-lithiation process in the pharma, and other reactions in food and drink industry, particularly related to micro-reactors and reactors with baffles and static mixers (Chen et al., 2015; Feng et al., 2017; Navarro-Brull et al., 2019).
- Good Manufacturing Practices have to be adapted/reinvented for some industrial domains since PI devices induce deep changes in the production habits.
- Unknown flexibility for further retrofit, debottlenecking or process modification. A too-highly optimized system can hardly be shifted from its optimal conditions.
- Lack of reliability of equipment suppliers (many start-ups) and end-user is wondering if they will still be on business in several years, supplying tech support and spare parts.
- Fast changing design of equipment (from the start-ups) which push the end user to wait for the next generation (technology is not stabilized yet).
Appendix 5. A short recount on past (Dutch) experiences

The Dutch community has demonstrated in multiple occasions to be ready to take on the challenge of innovation and investment in intensified technologies. We can leverage on our knowledge on earlier phases of substantial investments and rapid growth of the process industries in the past on different geographical locations, with the objective to identify the drivers and which points of engagement to influence basing on success story, as it is the case for The Netherlands.

The Netherlands may also serve as a case study to illustrate and better understand why companies are hesitant to embark on investing in new intensified technologies that experts on PI advocate. This text by no means has the ambition to fully describe and analyse the Dutch case. It does however have the ambition to serve as an example of how the PI community can study the target group, the process industries, to find new ways of engaging and influencing people working in the sector and putting them on the PI track when it is pertinent.

In the Netherlands the big expansion of the process industries kicked off with the discovery of one of the biggest worldwide reserves of natural gas on July 22nd 1959: 2800 billion cubic meters of gas in Slochteren in the north of the country. The first and soon leading question at that time was how this huge amount of gas could be brought to value as soon as possible, since in those days coal was believed to remain the main energy carrier for some time, soon to be followed by nuclear energy. People therefore assumed that natural gas value would drop to zero very soon.

This discovery attracted many multinational process industries that invested in process plants, using the newly found cheap gas as feedstock or as fuel for their plants. The Dutch government helped with advantageous tax rates and generous long-term gas contracts. Investments accelerated until late in the mid 70’s, when a period of transition into consolidation of production capacity started. Next to consolidation in this phase the process industry also matured in terms of number of product grades, quality and emissions control. In the 80’s and 90’s the industry kept growing at a steady yet lower rate than in the early days up to the point where we are now: the second biggest chemical industry in Europe after Germany in terms of energy usage. Fundamental questions are: what were the economic drivers? What were the main characteristics of the stakeholders in each phase that made them successful? How was innovation perceived? What was the most important point of every meeting in industry? Answers to these questions are divided by each decade until present day.

In the 60s ultra-cheap feedstock/fuel in combination with fast growth of product demand and a mild tax regime were the main economic drivers. People making the difference in those days were quick in decision making, bold and eager to build and operate. Innovation was seen as a useful tool to get the latest technology which enabled competition with foreign producers. Meeting construction targets and starting up as soon as possible were #1 agenda items.

In the 70s the world underwent two energy crises. The effects of acid rain and other types of pollution became visible. Margins between feedstock and product remained the economic driver but environment and— to a lesser extent— energy demand started to become a financial burden. Successful people in this period were the ones that could master the combination of running business-as-usual with managing environmental issues: the most important point during meetings. Innovation for existing production facilities became less important; innovation to solve emission issues could count on keen interest from companies.
In the 80s and 90s the process industries matured and kept growing at a steady pace. There was a shift of environmental issues from the periphery to the core of production processes: “if we do not make it, we do not have to remove it”. New elements became important: quality control, process safety and manufacturing cost. The economic drivers remained the same. Successful people now were those who could play the game on multiple fields. Innovation became less important, and replaced in meeting agendas by cutting cost and boosting sales prices by quality control.

The 00s and 10s became the decades in which the art of maintenance became the main tool to postpone investment and to keep plant reliability high at the same time. This period also experienced the massive and indelible appearance of the financial stakeholder who demanded high profits from companies each quarter. The economic driver changed from a natural one—adding value to a feedstock by producing a value-added product—into an imposed law: you shall make maximum profit every 3 months and long-term perspectives lost importance. Arguably, these were the decades in which safety and risk were at the forefront of every company’s agenda. Those who enabled the largest output in kilograms at the lowest cost, without any significant operational risk, were the most successful, since they maximized profits for stakeholders. Innovation was perceived as negative because it was seen to involve operational risk and to be costly.

The PI community has now two (non-excluding) options: transform the set of advantages of PI technologies into a package that is attractive to modern stakeholders and/or convince governing powers that implementing PI and updating chemical plants is key to meet sustainable development goals.
Appendix 6. Methods or steps to apply PI.

Appendix 6.1. BHR Group methodology
We presented this methodology in Appendix 3.6 from (Reay et al., 2013). The method is adapted from the BHR Group Ltd, and published on the Britest website.

Appendix 6.2. Twente steps to decide when to use PI.
This methodology was first presented in (Rivas et al., 2018). It consists on a step-by-step procedure to assist in the decision-making of whether to intensify or change a given process. Step 2 is an important moment, where the relevance of factors (technical or economical parameters) should be identified or agreed by experts (Appendix 3.1 for more details).

The intensification factor IF is a number that can be calculated with modular interchangeable evaluation criteria or factors (F). It is possible combine qualitative and quantitative factors. The IF number can be calculated at different levels, such as at the laboratory (researchers to comparing one setting change), at the plant or equipment level, or at the managerial, consumer/commercial level. The individual factors can be as many as needed, or based on the available information. The IF can be applied at all scales in the PI strategy, e.g. molecules, structures, unit, PSE, etc, and there is freedom to couple the qualitative aspects to costs when required.

Step 1. Select Objectives
Factors, parameters based on drivers (efficiency, profit, eco-impact,...).
Define exponent δ value based on desired/unwanted increase of F.

Step 2. Establish broad context
Societal, economical, ecological,...
Ensure good quality of sources, controllability,...
Re-assess parameters from Step 1 based on new intensification solution.
Re-assessment defines F values (if no experiment available).
If experiments are possible, obtain empirical F values.

Step 3. Apply IF Method
Considering empirical or estimated F1 and F2

Step 4. Select most relevant IFi values
Rank IF: considering empirical or estimated F1 and F2.
If possible, split in a) technically feasible, b) costs, commercial potential, etc.

Step 5. Propose Intensification Solution
Make a forecast based on Steps 1 and 2.
If no experiment available in Step 2, make experiment for validation.
If Step 2 was based on experiments, decide to continue or not with intensification.

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Appendix 6.3. Modelling examples

Subjects such as modelling and simulation are often postponed until graduate courses, hence too late to attract undergraduate students into this field. The understanding of fundamentals with first-principle models is a very first step in the design and knowledge of process intensification technologies.

An example where this has been successfully accomplished is the undergraduate-level textbook titled Introduction to Chemical Reaction Engineering authored by University of Toronto faculty (Missen et al., 1998). Fundamentals that are relevant for PI of reactor design, such as batch versus continuous and stirred versus plug flow, and of reaction engineering, such as parallel and series reactions, age distribution, reaction extent and selectivity, and transition state theory, were introduced alongside practical modelling examples that run on the accompanying software E-Z Solve (IntelliPro, USA). This was a simple script-based program that solved sets on non-linear algebraic equations and differential equations, and several examples of syntax were included in the textbook.

Assumptions and simplifications might be needed to model a system that in reality involves different time and length scales (Charpentier, 2010; RAPID, n.d.). Yet, computational fluid dynamics facilitated the fast evolution and applicability of static mixers (Ghanem et al., 2014), for example. To understand the difference between diffusion and advection of chemical species (Figure A6.3.1) we can instead use the approach known as inquiry-based learning (Milanovic and Eppes, 2016).

![Figure A6.3.1. Simulation results using COMSOL Multiphysics to interactively teach the difference between convective flux (cyan arrows) and diffusive flux (red arrows); grey gradients indicate concentration. Source: https://www.comsol.com/multiphysics/convection-diffusion-equation](https://www.comsol.com/multiphysics/convection-diffusion-equation)

With this methodology, a student can interactively visualize how to intensify a process by modifying the geometry of the channel, the diffusion coefficient or the velocity (i.e. increasing the Peclet number). Some students will eventually self-discover a static mixer (Figure A6.3.2), one of the most versatile process intensified technology (Keil, 2018; Kiss, 2016; Towler and Sinnott, 2013). With this example we can see how the concepts behind leading-edge PI technologies can be now introduced early in curricula.
Figure A6.3.2. COMSOL simulation of a static mixer for laminar flows. Intensification of mass-transfer can be illustrated with the concentration gradients (left) and concentration profiles (right). Source: https://www.comsol.com/multiphysics/convection-diffusion-equation
Declaration of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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