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Process intensification education contributes to sustainable development goals. Part 1

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ABSTRACT

In 2015 all the United Nations (UN) member states adopted 17 sustainable development goals (UN-SDG) as part of the 2030 Agenda, which is a 15-year plan to meet ambitious targets to eradicate poverty, protect the environment, and improve the quality of life around the world. Although the global community has progressed, the pace of implementation must accelerate to reach the UN-SDG time-line. For this to

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happen, professionals, institutions, companies, governments and the general public must become cognizant of the challenges that our world faces and the potential technological solutions at hand, including those provided by chemical engineering. Process intensification (PI) is a recent engineering approach with demonstrated potential to significantly improve process efficiency and safety while reducing cost. It offers opportunities for attaining the UN-SDG goals in a cost-effective and timely manner. However, the pedagogical tools to educate undergraduate, graduate students, and professionals active in the field of PI lack clarity and focus. This paper sets out the state-of-the-art, main discussion points and guidelines for enhanced PI teaching, deliberated by experts in PI with either an academic or industrial background, as well as representatives from government and specialists in pedagogy gathered at the Lorentz Center (Leiden, The Netherlands) in June 2019 with the aim of uniting the efforts on education in PI and produce guidelines. In this Part 1, we discuss the societal and industrial needs for an educational strategy in the framework of PI. The terminology and background information on PI, related to educational implementation in industry and academia, are provided as a preamble to Part 2, which presents practical examples that will help educating on Process Intensification.

Contents

1. Introduction 2
2. Semantics and quantification of PI 3
3. Limiting factors for PI technologies education and commercialisation 4
4. Process intensification education initiatives 6
   4.1. Inside academia 6
   4.2. Outside academia 6
5. Identifying key enablers for commercial scale PI solutions 7
   5.1. Education as a key enabler of PI deployment into society 7
   5.2. Other enablers of PI deployment 8
      5.2.1. Digitalisation 8
      5.2.2. Electrification 8
      5.2.3. Success stories as case studies 8
6. The role of governments, for-profit and non-profit institutions 9
7. Conclusions and recommendations 10
   Acknowledgments 10
Appendix A. Key outcomes and focus points of the workshop “Educating on Process Intensification”, 2019, June 3rd-9th, Lorentz Center Center (Leiden, NL) 11
Appendix B. List and details of places where PI is or has been applied (non-exhaustive) 11
   Universities (in alphabetical order) 11
   Massive Online Open Courses (MOOCs) 12
   References 13

1. Introduction

From June 3rd-7th, 2019, a group of experts from academia, knowledge-sharing platforms, government agencies, national laboratories, and industry met at the Lorentz Center in Leiden[1], The Netherlands, to identify strategies to target excellence in chemical engineering education by focusing learning on process intensification (PI) as a key enabling tool to achieve the United Nations Sustainable Development Goals UN-SDG (Šustainable Development Goals,” 2019). The UN-SDGs build upon decades of work by the UN in developing strategies to improve the quality of life and to protect the planet.[2] Notably, the chemical engineering discipline already addresses many goals that tackle climate change, clean water, air quality, affordable, and clean energy, and sustainable economic growth.

From the discussions at the Lorentz Centre, it was clear that academic and industrial specialists tend to confuse PI with process optimisation that relies on the application of existing concepts to improve performance. The former is the application of new principles to new or existing processes with a broader focus than just improving performance and minimising energy requirements. While optimisation aims to achieve incremental improvement in yield/conversion/processing cost by, e.g., changing the catalyst/solvent/additive concentration or adjusting temperature/mixing rate/residence time, PI aims for more significant improvement e.g. at least 2–3 orders of magnitude volume reduction by complete overhaul of the process from batch to continuous (Ramshaw, 1985), or to address insuperable challenges with emissions or safety. Arguably, PI and process optimisation are complementary because an intensified technology will often continue to benefit from process optimisation after its implementation.

Over the last century chemical engineers have developed modern technologies to produce a multitude of chemicals, fuels,

[1] https://www.lorentzcenter.nl/lc/web/2019/1103/info.php3?wsid=1103&venue=Oort

[2] This blueprint for sustainable development began in 1992 with the Earth Summit in Rio de Janeiro, Brazil, where many nations adopted the Agenda 21, to improve livelihood, quality, and sustainability. The Millennium Summit in New York in 2000 followed this multilateral agreement with the objective of ending extreme poverty by 2015. The Johannesburg World Summit on Sustainable Development in South Africa in 2002 also embraced the Agenda 21 and established multi-lateral partnerships to reaffirm the commitment to eradicate poverty and protect the environment. In contrast to the previous agreements, the 17 sustainable development goals call for synchronized multilateral actions from developed and developing countries to end poverty, improve education, health, reduce other deprivations in parallel with environmental protection and climate change.

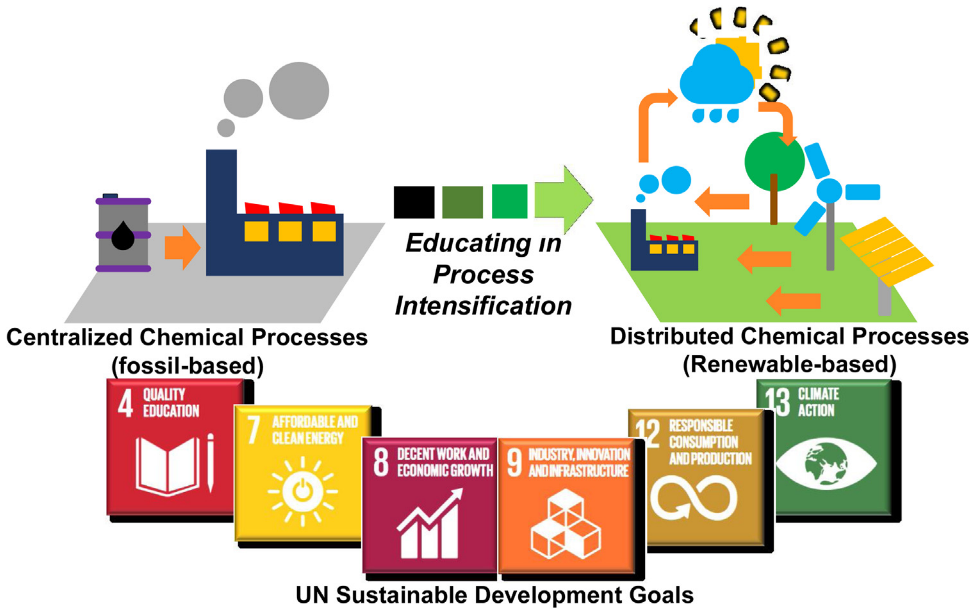

Fig. 1. Interplay of education on process intensification and the United Nations Sustainable Development Goals. The chemical industry must change drastically to contribute to sustainability.

commodity chemicals, fertilizers, pharmaceuticals, and materials that facilitated the social expansion and economic growth of industrialised countries. While we expect that chemical engineering will contribute to the UN objectives, applying traditional process optimisation and designing strategies will not deliver these changes fast enough (G. J. Harmsen et al., 2004). Furthermore, modern chemical industrial processes are conducted in large integrated chemical complexes with a limited degree of freedom to transition from fossil-based feedstocks and energy vectors to renewable resources (Resasco et al., 2018). To achieve the UN-SDG requires a paradigm shift with respect to the chemical industry raw materials, energy sources, and scale (centralised vs. distributed) (Stork et al., n.d.) (Fig. 1).

In this context, PI strategies offer changes in process efficiency and feedstock/energy transition. This potential has been recognised by technology providers, end-users, and policy makers. For instance, in 2006, SenterNovem, an agency of the Netherlands' Ministry of Economic Affairs, which implements sustainability and innovation-based programs on behalf of the government, defined the benefits of PI as follows: (1) energy savings in the range of 20–80 %, (2) capital and operational expenditures (CapEx and OpEx) savings from 20 % to 80 %, (3) chemical inventory reductions from 10 to 1000 times and (4) a relevant improvement in yield and selectivity (Ëuropean Roadmap for process Intensification," 2008; Reay, 2008).

To initiate this transformative process, educational PI programs must target renewable energies and feedstocks that correspond to the following US SDGs: ("Sustainable Development Goals," 2019) ***(1) quality of education (SDG-4)*** because educating on PI allows learners to acquire knowledge to develop more efficient and sustainable technologies; ***(2) affordable, clean energy (SDG-7)*** because PI enables energy savings in large-scale industrial processes and more compact and cost-competitive processes; ***(3) decent work and economic growth (SDG-8)*** can be attained because PI fosters opportunities for economic growth in developing and developed countries, thanks to the higher productivity and resource efficiency for medium and small scale plants; ***(4) industry innovation and infrastructure (SDG-9)*** can be boosted by PI because it enables cost-effective upgrading of old industrial infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and processes; ***(5) responsible consumption and production (SDG-12)*** because PI can support the development of environmentally sound management of chemicals and their by-products throughout their life cycle by improving process safety, and reducing waste generation; and finally, **(6) climate action (SDG-13)** since PI can accelerate the incorporation of renewable energy into existing chemical industrial plants, thus reducing greenhouse gas emissions (e.g. with electrochemical reactors, electrical heated micro-reactors, using biomass, etc.).

New generations of scientists and engineers need tools to implement urgent changes to the chemical industry. This paper details a summary of the outcomes we gathered at the completion of the workshop of the Lorentz Centre, in which most of the authors participated. In Appendix A we provide the short-term and long-term scope of the workshop we envisioned during its conception phase, as well as the main discussion topics. The main conclusion of the Lorentz Center Center workshop was that to best serve industry and therefore society, our educational system must respond quickly to this ongoing paradigm shift of the chemical industry. In this paper, we highlight PI fundamentals and identify the main challenges to implement PI in the chemical industry. Then, we detail the initiatives undertaken in industry and academia to improve learning of PI. Finally, we discuss technology enablers to deploy PI commercially and the role of governments, nongovernmental organisations (NGO), and private enterprises.

2. Semantics and quantification of PI

The literature includes a wide range of PI definitions, corresponding to different research and technological areas. For instance, PI was defined in 1995 as any process design that reduces the size of a chemical plant by a factor of one hundred, while maintaining a target production objective (Ramshaw, 1995). A few years later, PI was proposed as any chemical engineering development leading to a substantially smaller, cleaner, and more energy efficient technology (Stankiewicz and Moulijn, 2000; van Gerven and Stankiewicz, 2009). All definitions target improvements that are beyond the reach of traditional engineering optimisation and incremental research and development, with innovative equipment or methods solutions.

A widely used framework is the classification of PI into four domains of action: spatial, thermodynamic, functional, and temporal (van Gerven and Stankiewicz, 2009). This classification is complemented by the four PI principles: (a) maximising the effectiveness of intra- and intermolecular events; (b) giving each molecule the same processing experience; (c) optimising the driving forces, and maximising the specific areas to which these forces apply; and (d) maximising synergistic effects between partial processes (Fig. 2). This classification, is independent of a particular process or equipment and one of the most valuable aspects of it is its applicability at different scales, from the molecular processes, through microfluidics, to macroscale (reactors), and up to the mega- scale (plants, sites, enterprises) (Moulijn et al., 2008). The framework was first suggested in 2009 (van Gerven and Stankiewicz, 2009) and further elaborated and illustrated in a recently published textbook (Stankiewicz et al., 2019).

We have revisited the semantics of PI, where the "I" could represent either 'Intensification' or 'Innovation', and we provide more elements to understand how to apply it effectively:

1) **PI is an approach "by function", a departure from the conventional process design by unit operation**. In a design approach based on PI, process elements such as "reactor", "heat exchanger", and "distillation column" for instance, become "reaction", "heating", and "separation", thus shifting the focus from the process unit to a function that can be combined with others and achieved not just by selecting a known operation unit. (Kaiser et al., 2018). By looking at function rather than unit operations, it *becomes possible to design multifunctional or hybrid PI units* that enable the objectives of PI to be achieved e.g. the concept of reactive distillation —one clear example where this combination has been demonstrated commercially. PI is mainly based on increasing rates of mass and heat transfer, and their combination, with the objective of maximising the interfacial surfaces, reducing diffusion pathways (micro devices, combining several functions in one apparatus, heat recovery systems), increasing field gradients (strong gravitation fields, electric and magnetic fields, ultrasound etc.) i.e. exploiting driving forces that are "non-traditional" within chemical engineering.
2) **PI focuses not only on the process itself, but also on what happens "outside or as a consequence of the process"**. The unit-operations approach offers ways of increasing yield and selectivity. However, those enhancements generally cannot be achieved without increasing the degree of complexity of the chemical processes, the safety concerns, the inventory required, and thus without repercussions on the environment (Etchells, 2005). On the other hand, PI offers a unique way of designing cleaner, more efficient and safer processes by accurately matching the process requirements (such as mixing, heat and mass transfer, reaction time needed for a desired conversion) with those relevant capabilities of equipment and methods, which are based on radically different concepts. Finding a PI solution to a processing problem essentially involves a match-making exercise relying on knowledge-based engineering database, an example of which has been developed as part of the recently completed EU-SPIRE Intensified by Design (IbD) project (http://ibd-project.eu/). PI therefore involves a bottom-up design approach that allows greater flexibility in meeting the fundamental needs of the process. If all principles of PI are followed, then it is possible to develop more sustainable processes based on green chemistry principles (Boodhoo and Harvey, 2013).

While the potential of PI to help achieve the UN-SDGs is clear, its implementation in the education and industrial communities is still insufficient due to multiple challenges. In the next section, we discuss the main limiting factors that must be addressed within education and commercialisation to implement PI technologies in the chemical industry.

3. Limiting factors for PI technologies education and commercialisation

The implementation of a new paradigm, such as PI, faces similar challenges to those encountered when a new equipment or process is being considered to replace an existing one. In the scientific, industrial or commercial activities, decisions are regularly taken to find optimal conditions. Maximising profit, safety or social acceptance is a triple pillar reason to modify an existing process or system, e.g. re-designing equipment or investing in a new technology, which typically requires optimising the alternatives under specific constraints (Ben Purvis et al., 2018). Moreover, the integration of various technical, economic and environmental indicators, as well as quantitative and qualitative information, has been a bottleneck, particularly for the broader implementation of PI. This is because PI inherently requires a revision of a whole process as opposed to a limited optimisation. The degree of complexity of the "decision" strongly determines whether its practical implementation will be adopted by stakeholders. The interested reader is pointed to publications addressing methodologies, concepts of local and global intensification, environmental impact, accidental risks, and ways to quantify PI (Barecka et al., 2017; Kaiser et al., 2018; Etchells, 2005; Reay et al., 2013; Commenge and Falk, 2014; Portha et al., 2014; Rivas et al., 2018; Sugiyama et al., 2008; Keil, 2017).

The main challenges perceived by industry and how PI is helping to address them were discussed during the recent International Process Intensification Conference (IPIC2) in May 2019 in Leuven. The discussion notes will be forthcoming in RSC's Reaction Chemistry & Engineering. The principal drivers for industry to embrace PI practice are related to increasingly stringent environmental restrictions requiring more **sustainable processes**, the need to produce more with less, and more **efficient operations** along with keeping a **profitable business** despite regulations.

Lack of success stories: How long does it take PI technologies to transition from the design stage to industrial application? The demonstrated success of PI technologies appears to vary from a minimum of 10-years to more than 30-years, whereby the development comes from both academic or industrial R&D, and pilot phase. The ultimate deployment time is influenced by several aspects such as novelty, cost of implementation, and amortisation of existing equipment. Given the early stage of development of most PI technologies, success implementation stories are scarce, which causes industry decision-makers to be justifiably doubtful about the value and credibility of PI technologies.

Convenience of unitoperations-oriented disciplines: If PI technologies are actually as lucrative as promised, why don't we teach them in engineering curricula? This is linked to the historical success of the original paradigm in chemical processing — unit operations. The concept of a unit operation capable of carrying out a specific transformation (mixing, heating, reaction, separation, etc.) was introduced at the turn of the 20th century. Indeed, process design by unit operations[3] appeared in academic process engineering education programs and applied in industry in 1916 (Little, n.d.). By splitting phenomena into distinct physical pieces of equipment, the

[3] The term Unit Operation was introduced by A. D. Little in 1915

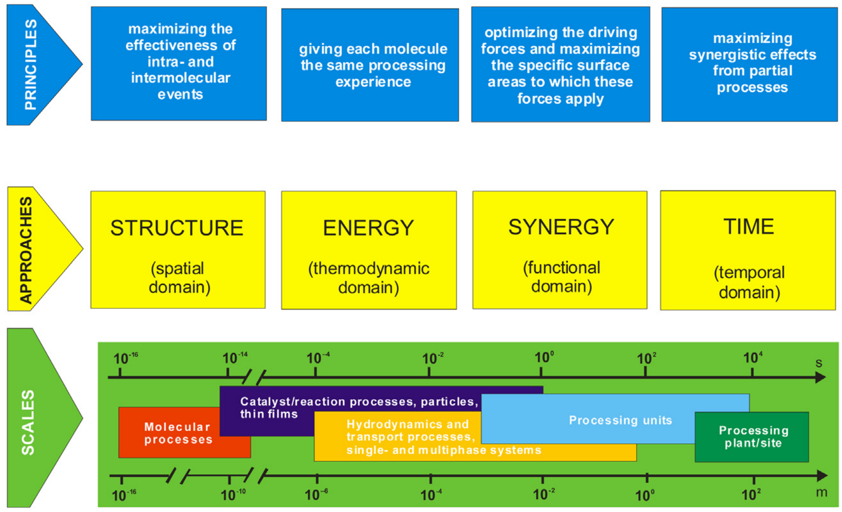

Fig. 2. Fundamental view on process intensification divided by principles, approaches, and the scales to which it applies. Reprinted with permission from Tom Van Gerven and Andrzej Stankiewicz, Ind. Eng. Chem. Res. 2009, 48, 5, 2465-2474. Copyright 2009 American Chemical Society.

application of unit operations endorses the systematic design and operation of a broad set of chemistries without massively relying on computational solutions and modelling. It was only 50 years later that the more mathematically rigorous and fundamental physics-based approaches became standard subjects to educate chemical engineers. However, since classical unit operations were still very successful, there was no urgent need to adopt unknown tools in chemical engineering, such as computer modelling, to radically redesign unit operations. The new formalism for chemical engineering was instead used to optimise and better understand the landscape of hardware that already existed.

Conservativism in upper management: Industrial habits are difficult to change once a process is successful and remains profitable.[4] Moreover, professionals who spend several years in industry may be reluctant to embrace new design philosophies because their managers focus on profit health and safety, and continuous (but marginal) improvement. It is not uncommon that managers only get excited once a competitor announces an introduction of something truly novel (the rush to be second paradigm). Furthermore, training personnel on new equipment represents an investment of resources and time. Here, once again, education plays the role of an accelerator at all levels for the uptake of PI in industry and its acceptance by the general public. Implementing PI in the BSc and MSc/MEng curricula represents a bottom-up strategy to speed up PI penetration in industry; a broader education should allow younger minds to evaluate the merits of PI in later stages of their careers.

Avoiding risk: In both European and North American industry, the main challenge today is to keep the existing plants in operation and to continue to produce. Hence, PI should be directed at making a critical improvement in those existing assets, while minimising down time and the technology risks during the start-up of the intensified process. Companies might also have assets in developing countries where the challenge is different, as new plants have to be built. But, there the difficulty is to implement a completely new technology, staff the facility with qualified individuals, and maintain operations in a highly competitive environment. In addition, the chemical industry is risk-averse, and the public would not accept industrial accidents happening frequently. And this risk aversion in the technology development is a big barrier to implement PI. As an example of the large-scale petrochemical complexes, the financial risk of introducing any significant change, let alone a more radical one like PI, is tremendous even if e.g. the residual risk of the new technology not working is as low as 0.1 %. Interestingly, the UK Health & Safety Executive supported PI from the safety/risk mitigation viewpoint, particularly for offshore processing plant. This was in part spurred by the Piper Alpha disaster in the North Sea (Etchells, 2005).

Supply chain fragility: Connected to the previous two challenges, for example, using an alternative feedstock/catalyst/reactor would mean a new supplier, that might be unique, when there are multiple suppliers for the established process. The business will ask to have also a long-term commitment or security on the supply as the plants are usually built to last more than 20 years. Understandably, there will be reluctance to depend on suppliers that are either too unique or without a strong track record.

Only in a few cases, a reduced inventory of the plant (and so potential risks) has been a driver to implement new technologies, e.g. offshore plants. Many concerning chemicals are still produced in batch processes, merely for economic reasons. For example, stirred tank reactors can be employed to generate several products, therefore many companies have them, and are fully depreciated. It is hard for a new process, for which the whole production line requires capital investment, to compete with depreciated equipment. In addition, there are two main types of businesses: the cash machines and the growth machines. The cash machines have to produce, and limited resources are allocated to improving it.

Perceived scalability issues: Traditional chemical engineering achieves profitability by minimising capital expenditure (CapEx) and operating expenditure (OpEx) by building larger facilities (stick-built) and reaching economies of scales by applying well-established correlations and scale-up factors. PI promises equipment orders of magnitude smaller and combining more than one function in a single unit. Traditional economic models do not apply to PI equipment scale-up. However, investors search for sturdy financial forecasts to reduce the risk of their assets. New, economic models should calculate the investment cost of intensified technologies. Two new paradigms in this sense are "numbering-up" or "scaling-out" and "economies of manufacturing learning" (Henderson, 1972; Weber and Snowden Swan, 2019).

To overcome these issues several important steps have been taken in the academic and industrial communities. In the next sec-

[4] It is worth pointing out that the conservatism is often resting with the contractors, not the users of the processes, who are keen to improve them. The classic selection of shell-and-tube heat exchangers in cases where a PCHE might be viable is a case in point.

tion, different educational initiatives to accelerate PI deployment that have been pursued in industry and academia will be discussed.

4. Process intensification education initiatives

4.1. Inside academia

The participants of the Lorentz Center workshop discussed several relevant questions: (i) is it more appropriate to introduce independent PI courses or incorporate PI content into traditional engineering courses? (ii) is there any specific teaching strategy that could help prepare students to better revolutionise the chemical industry to meet societal demand for sustainability? (iii) can we align the methods to educate professionals within industry with those used for undergraduate and graduate students?

Answering (i), PI courses are mostly offered to graduate students at relatively few universities around the world (see Appendix B). Even at those universities, PI is almost always offered as an elective and not as an integral way to carry out process design. There was a conviction among the Lorentz' workshop participants that PI should not be treated as a separate domain, but rather as the way Chemical Process Design is taught. The answers to (ii) are provided in Part 2. The answer to (iii) was that it is imperative we do draw from the ongoing teaching tools that are most successful, and educate at all possible levels, not only the specialists, but beyond the university walls: the general public.

The content of most chemical engineering curricula is still strongly influenced by the developments of the 1950s and 1960s in chemical engineering education, in which (reaction) engineering courses are organised to correspond to unit-operation and aimed at transport phenomena and understanding intrinsic and extrinsic behaviour of homogeneous and heterogeneous reactors, separators, mixers and heat exchangers (Baz-Rodríguez et al., 2016). In parallel, experimental laboratory practicums are also centred on these idealised systems, in which students apply the theory developed in class to real operation units. Moreover, only rarely do the courses deal with driving forces other than the thermal and concentration-dependent ones encountered in traditional unit operations schemes. While it is clear that to tackle more complex systems students should be proficient in the fundamental concepts of mass/heat transport, thermodynamics and reaction kinetics, it is difficult to understand why the more advanced and complex systems typically involved in PI are not covered in the course material. This in turn may be the cause why PI is almost always offered as additional course and "elective".

Notably, the interest in PI is growing worldwide, particularly in academic circles via research programs and projects. This resulted in a gradual penetration of PI into the curricula of universities (see Appendix B). Most institutions have not implemented educational PI programs, instead PI fundamentals are introduced in pre-existing course structures. Also, neither governmental entities nor engineering programme accreditation boards are mobilised to influence changes in the engineering and sciences curricula towards this direction.[5]

Such a disparity in the adoption of PI educational programs across the globe could be attributed to the relatively recent conception of this sub-discipline in the chemical engineering circles and the misconceptions in the true meaning of PI. The latter issue was addressed during the World Congress on Chemical Engineering WCCE2017, in Barcelona, where the first International PI Conference (IPIC) was held. In this venue, the chemical engineering community discussed the benefits of consolidating PI concepts, definitions, and philosophical framework in a dedicated session.

At the Lorentz Centre, the difference between process optimisation and PI was the focus of several discussions. While having different objectives, i.e. improving performance and minimising energy requirements (process optimisation) and revamping the process with innovative solutions (PI), the two complement each other. Indeed, PI analysis includes variables outside the reacting system, such as: emissions, chemical inventory, noise, footprint, safety, and other nuisances. Moreover, no guidelines to quantify "the degree of intensification" of a process, which are necessary to measure the extent of PI vs. traditional process engineering, have been established yet (Rivas et al., 2018). Clearly, understanding the PI principles is essential to overcome barriers and misconceptions in the chemical engineering community.

4.2. Outside academia

In 1998 Process Intensification Network Netherlands (PIN-NL) was launched as an initiative of the Dutch Ministry of Economic Affairs. Nowadays, PIN-NL is an independent network only funded by its members. Knowledge transfer from PI experts to stakeholders in industry has been the central theme right from the start. During its 21 years of existence PIN-NL has shifted emphasis from academic R&D to industrial applications of PI. All parties in the knowledge chain from lab to plant are welcome and contribute with knowhow. Currently, some 400 people – mostly from industry - are participating. Answering the question how to deploy PI technology as fast as possible, PIN-NL's findings differ slightly from those of EUROPIC. PIN-NL's key conclusion is, decision makers in industry are only going to make different choices in favour of PI if *all* of their needs and concerns are addressed. These include maintenance, investment criteria, availability of experts, process safety, risk management, regulatory affairs, etc. The impact of only technical PI knowledge transfer is limited and needs to be supplemented by knowledge about the mentioned areas.

The Process Intensification Network PIN (UK) was formed on 1 January 1999 (http://www.pinetwork.org/mins/apr99.htm). This network activity was supported by the Engineering and Physical Sciences Research Council (EPSRC), for the first three years. The network is currently based in the School of Engineering at Newcastle University, and its activities are directed with the assistance of a steering committee with industrial and academic representatives (see more in Appendix A).

The European Roadmap for Process Intensification identified in 2007 the limited awareness of available and developing PI technologies within the industry as the most important barrier hindering their practical implementations. A clear example of the lacking information at that time was the Roadmap Report on Rotating Packed Beds ("European Roadmap for process Intensification," 2008) (Chen, 2010). The report mentioned 12 commercial-scale applications of that High-Gravity technology in China alone, of which the European industry had been unaware. Triggered by the Roadmap, three European universities: Delft, Dortmund and Toulouse, developed an industry-driven platform for knowledge and technology transfer in the field of PI. The concept was supported by nine multinational chemical companies in September 2008, which helped establishing the European Process Intensification Centre (EUROPIC, www.europic-centre.eu), with the support for the entire value chain with high-quality information as its core activity. In 2019, EUROPIC had more than 20 international companies and created efficient interfaces between end-users, engineering companies and technology providers. In its activities, three mechanisms of knowledge transfer are exploited: (1) knowledge transfer from world's leading PI experts to member companies

[5] PI is not unique to chemical engineering. The electronics and telecommunications industries, as well as aerospace (the gas turbine) are examples where PI has brought benefits. In the Heriot-Watt University (Appendix B) PI has been taught as part of an Energy course, as well as to UG chemical engineering students.

via courses and tailor-made workshops, (2) knowledge transfer from the open information world to member companies leveraging technology scouting regular publications and databases of technical literature on PI, and (3) knowledge transfer between the member companies in so-called "expert meetings" in which PI specialists from the member companies meet and discuss various issues related to specific PI technologies, and their application barriers. Summarising, effective knowledge transfer presents a key ssuccess factor in boosting commercial implementations of PI. Currently, the R&D personnel in companies have simply no time for systematic studies of scientific literature or other information sources, therefore the importance of EUROPIC. PI champions in the chemical process industry are looking for "surprises" and "success stories" and use as foundations of specific cases inside their companies. The multifaceted knowledge transfer developed and practiced at EUROPIC brings such "surprises" and "success stories" to the light.

In 2016 the United States Department of Energy (DOE) called for and funded the establishment of a Manufacturing Innovation Institute on Modular Chemical Process Intensification for Clean Energy Manufacturing, which resulted in the creation of the **RAPID** Manufacturing Institute (www.aiche.org/rapid). The RAPID institute results from joint support of the U.S. DOE with a commitment of 70 million dollars and the member organisations (companies, universities, and non-profit research institutes and consortia) contributing another $85 million to the partnership over 5 years. In this new public- private partnership between the American Institute of Chemical Engineers (AIChE) and the U.S. DOE Advanced Manufacturing Office, the US government aims to (1) build a national community for PI and modular processing, (2) develop a curriculum to educate current and future engineers, operators, and technicians, (3) and fund and manage R&D projects to develop new process technologies that accelerate the commercial adoption of PI and modular process technologies. RAPID's industry members come from energy-intensive industries and range from small to large enterprises interested in creating greater opportunities for businesses, solve complex technology challenges, and unleash major savings in energy-intensive sectors (e.g. oil and gas, pulp and paper-making and other industries). RAPID and other Manufacturing USA institutes are focused on accelerating technology adoption to ensure competitiveness in U.S. manufacturing sectors.

More recently, the European Union (EU) financed the project Intensified-by-Design (IbD) as part of the Horizon 2020 initiative. This programme includes 22 partners from 8 countries in the EU with a total budget of 11 million euros to develop design and optimisation tools to catalyse the implementation of PI in industrial processes. The IbD aims at bridging the technological and knowledge gaps in PI for processes involving solid processing, which is relevant to many industrial processes (e.g. chemicals, pharmaceuticals, minerals, ceramics, etc.). This project has been structured to leverage the know-how of process designers, engineers, and operators with detailed physicochemical models, statistical information, and safety operation standards to identify the most attractive PI alternatives process. While this programme is primarily a flexible platform for PI designing, once launched and validated with industrially relevant processes, it will facilitate its utilisation as learning tool in many chemical industries. Within IbD there are six published Case Studies in the pharmaceuticals, ceramics, minerals and chemical sectors, including technologies such as the Coflore reactor and the Torftec fluid bed dryer("IBD RESULTS," 2019).

Notably, these initiatives in industry and academia reflect the relevance of PI in aiding the transition of the chemical industries to more efficient, competitive, and environmentally friendly processes. In this context, the participants in the Lorentz' workshop agreed that it is essential to train students and equip them now with the right tools because they could either a) be able to influence the upper management as they integrate in the job market or b) become decision makers themselves in 15–20 years.

5. Identifying key enablers for commercial scale PI solutions

5.1. Education as a key enabler of PI deployment into society

Chemical engineering courses in academic institutions –as all Science, Technology, Engineering and Mathematics (STEM) programs– strive to equip chemical engineers with most tools needed for problem-solving throughout their career. PI can be viewed as an extension of that toolbox (Fig. 3). There are three main areas of traditional chemical engineering education: **Area 1: Thermodynamics and chemical kinetics,** governed by fundamental laws of nature, are fundamental building blocks to enable PI. **Area 2: Heat/Mass transfer, fluid mechanics, reactor engineering, first-principle modelling–**Even when heat transfer fundamentals are unchanged, microchannel heat exchangers are "intensified" ver-

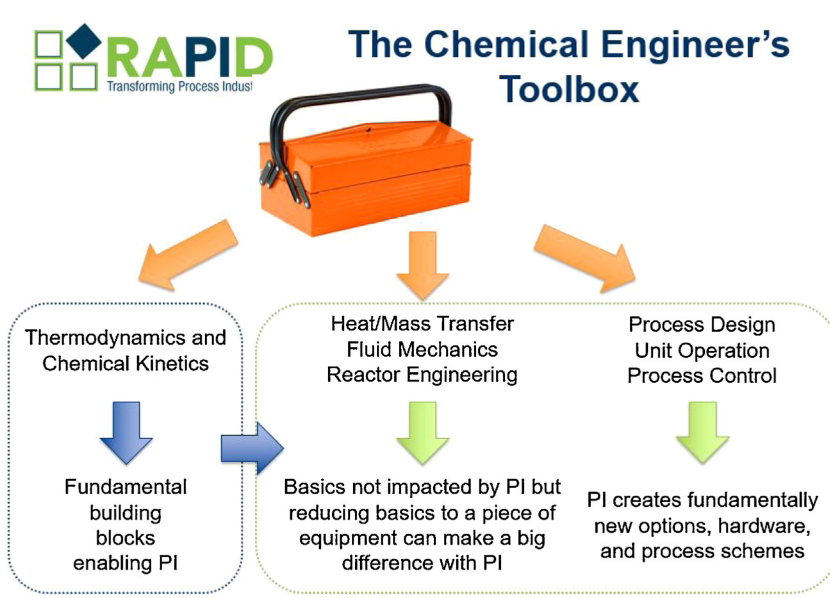

Fig. 3. The Chemical Engineer's Toolbox. Reproduced with permissions from RAPID Manufacturing Institute.

sions of classical designs, in the same way that a static mixer or a rotated packed bed are PI variants of classical stirred vessels or gravity settling. **Area 3: Process design, unit operation, process control, advanced design software** – PI creates fundamentally new systems to integrate, including hardware, and process elements. This translates into combination options where multiple conventional process steps are included in a single new intensified piece of hardware.

PI gives engineers an expanded toolbox to design processes that go beyond what unit operations have allowed (Fig. 3). In some cases, the new PI-enabled designs may break barriers that those traditional operations inadvertently imposed, resulting in more energy and raw material efficient—and therefore more sustainable—processes. We showcase below the fundamental differences and links between traditional "unit operations-oriented chemical engineering education" and "PI-oriented education":

Traditional Chemical Engineering Education: Today chemical and process engineering course structure typically follows traditional paradigms:

- Rooted in established textbooks and established reactor designs, tied to traditional unit operations that target economies of scale by scaling up by adopting scale-up factors (e.g. Chilton scale factor) in a stick-built approach to build ever increasing units (Chilton, 1950; Garnett, 1992; Garnett and Patience, 1993).
- Current chemical engineering education can, at times, be disconnected from industrial challenges (sustainability, efficiency and profitability) even though design projects are more and more focused on processes adopting renewable energy sources and limiting greenhouse gas emissions.
- While current chemical engineering education provides basic knowledge in kinetics and process control training, there is an opportunity to include more emerging disciplines, such as flow chemistry- to move from batch to continuous processing.

PI/sustainability focused Chemical Engineering Education: Instructors should emphasise training on:

- Providing context and tangible examples of cases where PI was implemented successfully (e.g. batch to continuous, modularisation, exploiting non-traditional driving forces) and show the potential outcomes to aspire to these goals.
- Promoting creativity and encouraging students to find knowledge beyond classic textbooks, such as in peer reviewed papers, patents, and conferences, as well as to propose or design processes, which differ from established solutions (Hamouda and Tarlochan, 2015; Noël 2019).[6]
- Training to innovate. Giving tools to explore ways to turn inventions into profitable solutions that can be implemented in industry. Some examples are provided in Part 2.
- Promoting and participating in initiatives bridging academy and industry, such as the workshop held at Lorentz Center (Leiden), EUROPIC, INDUS MAGIC, RAPID Institute. There are regular conferences, such as IPIC and European Process Intensification Conference, but need to be promoted and intensified as well.
- Improving basic skills. e.g., providing training in computer-aided process modelling and control that can lead to managing more complex systems (i.e. from batch to continuous); teaching to design and control flow reactor kinetics, kinetics modelling, etc.[7]

Links between traditional and PI/sustainability-focused Chemical Engineering Education: The participants agreed that to understand and learn PI principles a strong engineering background is fundamental. Therefore, a course on PI should preferably be offered to last-year undergraduate or graduate students, who already mastered the fundamentals of engineering as well as of the physics of non-traditional driving forces.

5.2. Other enablers of PI deployment

5.2.1. Digitalisation

An additional element that will play a decisive role in facilitating the penetration of PI is the digitalisation of the chemical industry. The availability of new platforms for fast and reliable real-time data sharing combined with artificial intelligence and future supercomputing capabilities will expedite the introduction of radically new chemistries, process designs, and process-operation/optimisation protocols. The transition to this so-called "Industry 4.0″ will provide excellent opportunities for the development of intensified chemical processing technologies, e.g. data analysis of current (non-PI) industry will help to identify excellent opportunities, which heightens further the need to prepare our students on PI.

5.2.2. Electrification

The ongoing transition of the chemical industry from fossil-driven to electrically-driven processes offers the opportunity to use PI principles to develop new equipment and processes. Renewable energy sources, e.g. solar and wind, have a natural variability and several approaches have been taken to deal with supply fluctuations. Strategies to store electricity in batteries are expensive infrastructure. Electricity storage by pumping water in dams is already implemented but has a limited capacity. Process-intensified electricity-consuming technologies, such as ultrasound, microwave, plasma, photochemistry, electrochemistry, etc., present a better alternative, since these technologies have the potential to decrease the electricity storage cost (whose availability is susceptible to daily and seasonal variations), improve the environmental footprint of chemicals, and improve the economics of the process. Moreover, these processes have a short start-up allowing fast response to seasonal and daily variability of electricity production, which is not possible with conventional chemical processes. However, this requires a mindset shift in the process industry, which is accustomed to constant and regular production.

5.2.3. Success stories as case studies

The commercial scale implementation of PI is rising. Static mixers are ubiquitous now. The commercial implementation is increasing. There are already more than 150 reactive distillation, 100 dividing wall column (DWC) distillation and 100 reverse flow reactors and implementations of microchannels reactors and high gravity absorbers are ongoing (J. Harmsen, 2010). Implementation of PI technologies also seems to be catching up in countries like China and India (especially in the oil and gas sector, and specialty chemicals sector). There are at least five new implementations of DWC in India in the last three years in the top three oil refineries of India (Reliance Industries Limited. Annual Report 2018-2019 n.d. ; "Top Dividing Wall Column Technology – a Novel Approach," 2019) (Ïndian Oil Corporation Limited. Annual Report 2018–19," 2019).

[6] In many study programs this is already the approach in traditional chemical engineering education. But the authors felt this should be maintained, and stressed even further.

[7] In several courses at the author's institutions, there are already courses with simulations in the traditional teaching using, for example, ASPEN plus. We stress the importance of extending its use to other softwares and modelling approaches.

Table 1
Comparison of different options to recover more medium-weight hydrocarbons (Indian refinery). Feed rate: 225 000 kg h^{-1}; weight fractions: $iC_4 + nC_4$: 0.45, iC_5: 13.97, nC_5: 15.59. Data from (Bhargava and Sharma, 2019).

Parameter	Existing process	Traditional Chemical Engineering approaches		Process Intensification
	Two-Column Sequence		Side-cut column	Dividing-wall column
	Depentaniser (existing)	Deiso-pentaniser (new)		
No. of trays	50	75	75	75
D column, m	4.6	3.7	4.6	4.6
Condenser duty, million kcal h^{-1}	14.6 30.2	15.6	18.7	19.1
Reboiler duty, million kcal h^{-1}	18.4 34.2	15.8	23.5	23.5
iC_5 Product				
Rate, kg h^{-1}	23 193		20 500	23 193
$iC_4 + nC_4$, wt%	4.36		4.91	4.36
iC_5, wt%	90.00		90.19	90.03
nC_5, wt%	5.45		4.72	5.45
nC_5 –Rich Side Draw				
Rate, kg h^{-1}	51 776		84 638	51 776
iC_5, wt%	20.30		15.25	19.98
nC_5, wt%	59.79		36.90	60.10
C_{6+}, wt%	19.91		47.85	19.92
Naphta Product				
Rate, kg h^{-1}	150 031		119 862	150 031
iC_5, wt%	0.03		0.02	0.13
nC_5, wt%	1.91		2.40	1.80
C_{6+}, wt%	98.07		97.58	98.07

The BPCL Refinery at Mumbai became the world's first commercial application of a top DWC. There are examples of the implementation of HiGee deaeration that have led to 10–20 times smaller-sized units for the same production capacity. A significant reduction in capital and revenue expenditure has also been reported ("Bharat Petroleum Corporation Limited, Annual Report 2018-192018–19, Page 86. (2019)," n.d.Bharat Petroleum Corporation Limited, Annual Report -19, Page 86, 2019Bharat Petroleum Corporation Limited, Annual Report 2018-192018–19, Page 86. (2019)," n.d.). Membrane Bioreactors and Loop reactors have found implementation even in Small and Medium-sized Enterprises (SMEs) ("Aarti Industries Limited. Plant Visit- 5th October, 2019," n.d.). Worldwide operating technology licensors have also started to intensify their processes: Johnson Matthey with new catalytic internals for steam methane reforming (SMR); Haldor Topsoe with electric SMR ("CATACEL SSR. Johnson Matthey, " n.d.; Van Ngoc Bui et al., 2011).

These successful commercialisation stories of PI equipment strengthen the need to insert PI in school curricula. It is interesting to note that none of the companies describe the technologies they use as PI or process-intensified. The reasons for this are unknown to the authors of this work. Plausibly, process optimisation (which is "normal chemical engineering") naturally evolved towards process intensification with this latter still being labelled as "process optimisation". Identifying these cases, which have passed to history as "process optimisation" successes rather than as "process intensification" ones, is key to showcase PI implementation rewarding technologies to both academia and industry.

An example (case study) through which we can demonstrate the difference between a traditional chemical engineering approach by unit operations and PI, among others, is the DWC. With this case study we also demonstrate the alignment of PI with some of the UN's SDGs. DWC is a PI approach by equipment that replaces multiple distillation columns to separate multi-component mixtures. In a DWC, a dividing wall separates a distillation column vertically into two sections. The section where the feed is located, separates the light and the heaviest components, while the section opposite to the feed (rectifying zone), separates the middle-boiling component. For instance, to recover medium-weight hydrocarbons from naphtha, a naphtha splitter separates first light and heavier naphtha. A depentaniser then separates the light naphtha into a C5-rich fraction and the rest of naphtha. A refinery in India wished to upgrade its process to recover more light weight hydrocarbons. They therefore compared four options: i) existing process; ii) addition of a deiso-pentaniser (traditional chemical engineering approach); iii) replacement of the depentaniser with a side-cut depentaniser (traditional chemical engineering approach) and iv) a dividing wall column (PI approach). Bhargava and Sharma report some of the data from this study (Bhargava and Sharma, 2019), which we summarise in Table 1.

The intensified approach by DWC aligns with the UN's SDGs in many ways. The equipment is smaller and lower in number compared to both the existing process and chemical engineering approaches to increase productivity (Table 1), thus translating into capital costs savings. This aligns with UN's SDG 9, i.e. "Industry, Innovation, and Infrastructure", which demands investment in infrastructure and innovation as crucial drivers of economic growth and development. Economic growth, together with decent work conditions is indeed the UN's SDG 8. Lower condenser and reboiler duties result in lower emissions, which aligns with the climate action of the UN's SDG 13. Clean electricity can power more easily equipment requiring smaller duties, thus increasing the chances of using clean energy to power chemical processes with affordable, clean energy (UN's SDG 7). Moreover, the study reported was implemented in India, a developing country. PI technologies have the potential to reduce poverty in those countries or regions that still lag behind in their economic and manufacturing infrastructure, thus helping reaching UN's SDG 1 of eradicating poverty. All the goals mentioned so far contribute to sustainable cities and communities (UN's SDG 11).

6. The role of governments, for-profit and non-profit institutions

With the exception of the United States, where the government is actively stimulating PI research and innovations through funding the RAPID institute, based on the participants' experience, i.e. in the Dutch, Belgian (Flanders), French, Indian, Mexican and Canadian landscape, governments are not actively stimulating PI research or innovations related to any specific technology. Government funding support is currently focused on the societal

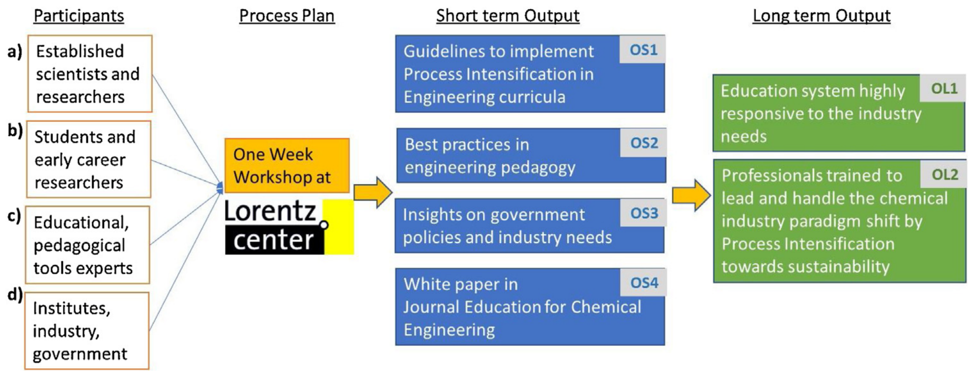

Fig. A1. Short term outputs (OS) and long term output (OL) of the workshop "Educating on Process Intensification", 2019, June 3rd-9th, Lorentz Center Center (Leiden, NL).

challenges of the 21st century that need to be addressed, such as energy transition and sustainability ("Missies voor de toekomst | Topsectoren," 2019) (Hoornaert, 2014). PI shapes up as a versatile approach to tackle societal problems because it crosscuts several technical disciplines and it can therefore leverage funding dedicated to different scopes, in particular reducing greenhouse gas emissions. Since it is accepted that PI can be a part of the solution for these societal challenges, we strongly believe that individuals and organisations interested in PI activities will need to focus more on societal added value of R&D to obtain funding from government programs. Currently, government should be seen as a representative of society in general, and consequently an interest in PI needs to be present among the general public. Past successful participations of the general public can be found elsewhere ("Artificial leaf as mini-factory for medicine, n.d.; "KU Leuven scientists crack the code for affordable, eco-friendly hydrogen gas, " n.d.).

One example where PI can leverage public interest at large is its potential to design processes that are far smaller, safer, and more environmentally friendly than traditional ones, in particular, when dangerous goods are involved. Through intensification strategies, inventories of dangerous goods can be reduced and when production and use of dangerous goods is re-located, transportation risks can also be avoided. Considering PI potential to reduce risks should therefore be part of the continuous improvement cycle to prevent major accidents, as required by the EU Seveso directive (Ševeso legislation - Industry - Environment - European Commission," 2019). Nevertheless, scientists could influence technical societies, to whose governance they have access, which could in turn influence government. Country and region-specific PI initiatives and other details can be found in Appendix B.

7. Conclusions and recommendations

The main discussions and original conclusions of the team of experts that gathered at the Lorentz Centre in the Netherlands in June 2019, have been consolidated in this work. We have identified key actions to maximise the potential of process intensification (PI), in particular through engineering education. PI drivers and the potential of PI have been demonstrated to meet most of the United Nations Sustainable Development Goals.

Even though the primary focus was "PI in chemical engineering", other disciplines that strongly depend on technological innovations can benefit from the analysis and historical recount provided in this paper. We see that the synergy between academia and industry efforts is the most efficient (and arguably the only way) to develop environmentally friendly and profitable processes.

We anticipate the development of new educational actions that can accelerate the penetration of PI in the industry and academia. This, combined with better advertised success stories, will assist in the decision-making process of "intensifying processes when needed". Some relevant questions, such as 'How to "intensify" PI teaching?' with lectures, peer instruction, group projects, virtual reality, laboratories and simulation are discussed in Part 2.

Declaration of Competing Interest

There are no conflicts to declare.

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Appendix A. Key outcomes and focus points of the workshop “Educating on Process Intensification”, 2019, June 3rd-9th, Lorentz Center Center (Leiden, NL)

See Table A1

Table A1
Subjects schedule and corresponding output, according to Fig. A1: short term outputs (OS) and long term output (OL).

Monday	Tuesday	Wednesday	Thursday	Friday
Setting the scene: Fundamentals Knowledge, and “schools” available	*PI-teaching for the industry:* Valorisation, innovation, value creation and spin-offs	*Experimental teaching:* Teaching the professionals of the future	*Governmental policies, initiatives* Expectation management; “what industry and society needs”	Wrap-up and Outline of the white paper
a) OS1 OL2	***d) OS1 OL1***	***b,c) OS2 OL2***	***d,a) OS3 OL1***	**a-d) *OS4* OL2**

Appendix B. List and details of places where PI is or has been applied (non-exhaustive)

Universities (in alphabetical order)

Name	Year introduced	Details
Delft University of Technology	2003	MSc course, currently based on the book “Fundamentals of Process Intensification” by Stankiewicz, Van Gerven and Stefanidis (Wiley-VCH). Includes 28 h of lectures and a case study project. https://ocw.tudelft.nl/courses/process-intensification/ Profs. A. Stankiewicz, T. Van Gerven, G. Stefanidis
Dortmund University	N.A.	The Laboratory of fluid separations offers courses such as Membrane processes and hybrid separation processes and Membrane processes and hybrid separation processes http://www.fvt.bci.tu-dortmund.de/cms/en/teaching/index.html Prof. A. Górak
Eindhoven University of Technology	2012	Dr. Timothy Noel – Chair Micro Flow Chemistry & Synthetic Methodology 1 BSc practical course: Two flow chemistry examples (2 × 1 day). MSc elective course “Micro Flow Chemistry and Process Engineering” Dr. John Van der Schaaf – Chair Chemical Reactor Engineering High Shear-High gravity-based Spinning disk technology is treated in Advanced Chemical Reactor Engineering Prof. Martin van Sint Annaland – Chair Chemical Process Intensification: Advanced separation technology (reactive separations, hybrid techniques)
Ensiacet Toulouse	N.A.	A third year (last undergraduate year) specialisation is offered in Energy and Process Intensification with the choice of four (4) different ientations: Design and analysis of intensified processes; Efficiency and energy logistics of industrial systems; Eco-Energy transversal course; Fluid, Energy and Process transversal course Profs. L. Prat, C. Gourdon
University of Guelph	2015	Graduate course Process Intensification Prof. E. Chiang.
Heriot-Watt University	Around 2008	Part of MEng Chemical Engineering and elective in the MSc Energy Studies course. Classed as a module, examined and a design project. Case studies incorporated in Reay et al. (Reay et al., 2013) https://www.hw.ac.uk/documents/pams/202021/B482-CEE_202021.pdf
KU Leuven	2009	Course (3ECTS) on Process Intensification Chair on Process Intensification Examples of large PI projects (coordinated by KU Leuven): • COSMIC (EU MSCA-ITN project): https://cosmic-etn.eu/ SIMPLIFY (EU SPIRE project): https://www.spire2030.eu/simplify
University of Lorraine (Nancy)	2000	More than 600 graduate engineers trained to PI, Prof. J.M. Commenge
Polytechnique Montréal	2017	60 to 90 undergraduate Chemical Engineering students exposed every year to the fundamentals of process intensification in the course of Chemical Reaction Engineering and Design Courses. Profs. D.C. Boffito, G.S. Patience

University of Applied Science Utrecht	2010	One of the topics of the Distillation course has been PI, serving mainly as an introduction for the students to the principles of PI and to get them thinking about different possible approaches to process and distillation design. In addition to that, several experimental PI setups, most notably a micro reactor and a SpinPro reactor are present, the latter of which is part of the curriculum since earlier 2019. Currently re-developing its sixth semester, designed around the theme of sustainable process innovation. There, PI will be given a large role, mostly in the process design course. Sustainability will also be the focus of a minor currently under development. J. van Gestel
Newcastle University	1970	Research into high gravity technologies such as rotating disk has been taking place at Newcastle as early as the 1970s. Process Intensification has been taught in the Chemical Engineering curriculum since early 1990s. PI module (5 ECTS) is currently taught as a compulsory module to between 70−80 students undergraduate and postgraduate students on the MEng in Chemical Engineering or MSc Sustainable Chemical Engineering. PI is also embedded in Plant Design Projects in the 3rd year of the BEng/MEng Chemical Engineering degree programmes.
University of Applied Sciences Offenburg	N.A.	Research Group "Lab for Product and Process Innovation (PPI)" Prof. P. Livotov
Twente University	2015	150 students have received PI fundamental knowledge, of which three course editions were mandatory with 5 ECTS, and one optional with 2.5 ECTS. Prof. D. Fernandez Rivas
Institute of Chemical Technology, Mumbai	2004	Several schools and workshops organised on Process Intensification; Center of excellence in process intensification Prof. S. S. Bhagwat
Indian Institute of Guwahati	At least 2013 onwards	Graduate course "Chemical Process Intensification" Prof. S. K. Majumder Detailed course description: https://swayam.gov.in/nd1_noc19_ch18/previewE lective for Chemical Engineering students
Indian Institute of Technology, Delhi in India	N.A.	Courses offered in Experimental characterisation of multiphase reactors; Modelling of transport processes; Advanced Transport Phenomena
University of Sydney	At least 2019 onwards	Offered as a major for undergraduate students: https://sydney.edu.au/courses/subject-areas/major/process-intensification.html
National Institute of Technology, Tiruchirappalli	2015	Elective for Chemical Engineering Bachelor students Details about topics covered on Page 77 of : https://www.nitt.edu/home/academics/curriculum/B.Tech-CL-2016.pdf Topics covered includes micro reaction technology, heat transfer and mixing in intensified equipment, Combined reaction and separation enhanced fields.
	2016	Elective for Chemical Engineering Master students For Chemical Engineering Master students course was first offered in 2016 https://www.nitt.edu/home/academics/curriculum/M.Tech-CL-CE-2016.pdf. The course code is CL631 Contents that are covered can be found on page 58 of :https://www.nitt.edu/home/academics/curriculum/M.Tech-CL-CE-2019.pdf

Massive Online Open Courses (MOOCs)

Name	Year Introduced	Observation
Delft University of Technology	2016	https://ocw.tudelft.nl/courses/process-intensification/
Indian Institute of Guwahati	2019	https://nptel.ac.in/courses/103/103/103103152/

Knowledge institutes

Europe

In EU projects (e.g. SPIRE projects) there is focus on developing teaching material and holding workshops to train students and employees in the new (PI) developments.

Intensified-by-Design (IbD®) SPIRE project (http://ibd-project.eu/)

The Intensified-by-Design (IbD) Project has created a holistic platform to facilitate process intensification design and optimisation in processes in which solids are an intrinsic part. The project has developed and upgraded methods for the handling of solids in continuous production units based, on the one hand, in the intensification of currently existing processes and, on the other hand, through completely new approaches to the processing of solids. A knowledge-based engineering database capturing a number of important PI technologies and methods has been developed as part of IbD to enable users to select and evaluate appropriate PI solutions for their processes.

Europic (see page 6).

United Kingdom

The Process Intensification Group (PIG) (http://pig.ncl.ac.uk/) in its current form is the World's largest Process Intensification Research Group with ~65 members (14 academics, 10 postdocs and visitors, remainder PhDs). They are world experts in rotating process technologies, heat pipe technologies, and oscillatory mixing technologies. Other key technologies for the group include: plasma processing, microfluidics/flow chemistry, and microfluidised beds.

PIN (UK) http://www.pinetwork.org : To maintain PIN as a forum where all those interested in the science, technology and application of Process Intensification can communicate effectively with others in the PI and related fields. To create an environment, based on meetings and other means of communication, where members can gain: • A knowledge and understanding of the science and technology of PI • An insight into the activities of the research community in the area of PI, including identification of centres of excellence in the field.

• A knowledge of the key needs of user industries as they adapt to the benefits offered by PI • Facilities for transfer of PI technologies between sectors

• A good knowledge of, and opportunities to participate in, research, development and technology demonstrator programmes, funded by consortia of members and/or national/international funding authorities

• A route to further education in the science & technology of PI and its applications.

There is also the Summer Science Exhibition organised by the Royal Society every year. It is an opportunity to showcase exciting research featuring PI to the public and especially to young people.

The Netherlands

PIN-NL: https://www.linkedin.com/groups/4321849/ stands for Process Intensification Network Netherlands. It is an independent network managed by a board consisting of experienced experts independent of either government or companies. Its focus as laid down in the Statutes is to enhance process sustainability via energy saving and feedstock utilisation. The PIN-NL network consists of about 400 people from every link in the knowledge chain from lab to plant: universities, knowledge institutes, consultants, engineering companies and end users of technology. Members in this network gather 3 times per year to share their thoughts, ideas, and progress on process intensification. Since 2010, about 150 presentations on PI have been organised, 50 % of which have been given by presenters from countries outside the Netherlands. 21 years of PIN-NL have taught its members that knowledge transfer is *not* the only key success factor to get PI deployed in industry. PIN-NL believes each of the following areas has to be addressed to meet the needs and concerns of CEO's enabling a choice for PI in industry:

- Corporate strategy; extension; outsourcing; prioritisation
- Plant maintenance; remaining lifetime of plants
- Investment criteria inside the company
- Unfamiliarity with new technologies in general
- Risk aversion
- Lack of expert personnel
- Finances
- Process safety
- Risk management
- Personnel management
- Staff
- OPEX (energy, feedstock, water, cooling)
- CAPEX
- Regulations
- Footprint
- Production technology

North-America

Canada

In Canada, Process Intensification Education remains an initiative that depends on individual professors either proposing graduate courses on PI (Prof. E. Chiang at the University of Guelph) or targeting it in their academic research (University of Guelph: E. Chiang, R. Santos; Polytechnique Montreal: D.C. Boffito, G. Patience, B. Blais; Dalhousie University: H. Quan). Senior engineering practitioners from academia, the public sector and private industry compose the Canadian Engineering Accreditation Board (CEAB), which accredits undergraduate engineering programs and set national standards for engineering education. To implement PI at the undergraduate level in Canada, companies will have to demonstrate their need for experts in PI and influence the CEAB, who will have to play a key role in its implementation in the engineering curricula.

USA

Rapid (see pages 18 and 21 and 26)

Mexico

In the academic sector, about 10 % of the universities teach elements of PI course in the last year of their programme. In the research sector, a few scientists maintain links with universities abroad, where they first learned about PI and have expanded part of their doctorate studies. The traditional support from the government to research actions through the Consejo Nacional de Ciencia y Tecnología (CONACyT) have been reduced drastically, and there is no specific PI initiative funded by the Mexican government to the best of our knowledge.

In the industrial sector, Mexico has an economy of USD 2.4 trillions, ranked 11th worldwide, traditionally seen as a manufacturing hub, the free trade between USA and Canada (1994) allowed it to export much more (in the chemical sector), through important groups such as: ICA, Mexichem, Indelpro, PEMEX Petroquimica, Vitro, Procter and Gamble, Akra, BASF, Du Pont, Dow Quimica, Peñoles, Petrocel, etc. Mexico has assimilated technology, to increase production, but has not leaped into the knowledge-based economy. The ANIQ (Asociación Nacional de la Industria Química), CAINTRA and Instituto para la Competitividad de la Industria Química provide some services, mainly focused on developing manufacturing, but not to innovate process design.

Asia and Pacific

National Chemical Laboratory (NCL), Pune, India is one of the National Laboratories under the Council of Scientific and Industrial Research runs the INDUS MAGIC (Innovate, Develop & Up-Scale Modular, Agile, Intensified & Continuous Processes & Plants programme for industrial collaborative projects. It also runs an Indus Scholar programme where students carry out projects based on MAGIC concepts. Workshops, training programs, seminars are also conducted (http://www.indusmagic.org).

China

Research Center of the Ministry of Education for High Gravity Engineering and Technology, Beijing University of Chemical Technology, Beijing 100029, China

Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China Chemical process

Scholarly sources and venues

There have been two broad and ongoing mechanisms for dissemination of PI concepts and technologies from an academic/research perspective.

One is the Elsevier peer-reviewed journal Chemical Engineering and Processing. The ninth issue of the 46th volume of this journal was a special issue on the 2007 European Process Intensification Conference (EPIC), and starting with this issue, the journal and its editors (Dr. Andrzej Górak, Dr. Gabriel Wild, and Dr. Andrzej Stankiewicz) adopted an extension to its title: Chemical Engineering and Processing – Process Intensification.

The second mechanism has been dedicated PI events, particularly those linked to the Working Party on Process Intensification of the European Federation of Chemical Engineering. These included conferences, colloquia and summer schools, hosted in several countries. Most notably, EPIC has had five editions (Copenhagen (2007); Venice (2009); Manchester (2011); The Hague (2013); and Nice (2015)), and has been succeeded by IPIC (International Process Intensification Conference) in Barcelona (2017) and Leuven (2019).

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