Education in systematic eco-innovation in environmental and process engineering

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Introduction

Engineering educators have understood the increasing demand of society and industry for higher qualification of graduate students in sustainable product and process development and innovation under comprehensive consideration of the environmental impact. Hanning et al. (2012) pointed out a gap between the competences in sustainable design obtained at the engineering universities in Sweden and the needs of industrial companies. Olsen et al. (2018) reported about the Life Cycle Assessment course at the Technical University of Denmark providing different levels of sustainability competences to the bachelor and master degree students. Perpignan et al. (2018) analysed the place of eco-design in curricula from secondary school to university and engineering school in France and provided recommendations for quality improvement of education for sustainable development.

Numerous approaches and methods have been developed in the last three decades to support sustainable and environmentally-friendly product and process development, such as Life Cycle Assessment, Eco-Design, Green Process Engineering, Process Intensification, and Process Design for Sustainability. However, these methods frequently don't belong to the mandatory components of engineering studies today.

In comparison with systematic eco-design tools to assess and overcome negative environmental impacts, only the Theory of Inventive Problem Solving TRIZ (VDI, 2016) offers methods and tools for identification and elimination of engineering contradictions and helps enhance the inventive skills of engineers. Cascini et al. (2008) reported the enhancement of thinking and problem solving skills of engineering students with TRIZ. Belski (2018) compared results of numerous international studies and proposes that embedding of simple TRIZ methods for problem analysis and idea generation into existing discipline subjects can improve creativity and innovation skills of students.

Thus, many researchers proposed to apply TRIZ for the domain of eco-innovation in the chemical industry (Ferrer et al., 2012) or eco-design (Russo et al., 2013). The recent publication of the authors (Livotov et al., 2019) chronologically reviewed 66 papers on eco-innovation with TRIZ methodology since 2000. None of them systematically covers the aspects of education at the universities. Educators from nine universities in Australia, New-Zealand, France and Germany (Belski, Cavallucci et al., 2018), summarise their experience in teaching TRIZ with recommendations on how to establish the education in new product development and systematic inventive problem solving or to improve its performance. Badran (2007) investigated the relationship between creativity and engineering education and outlined the necessity of special courses and activities that would enhance innovative skills of graduate engineers. Anderson (2013) outlined the fact that innovation methodologies are seldom taught comprehensively at universities and require a new interdisciplinary teaching approach.

In the field of eco-innovation many process engineering curricula still contain too few offers for a structured development of new solutions providing significant environmental advantages. Thus, engineering graduates and specialists frequently lack the advanced skills and knowledge required to run eco-innovation systematically. Here, we propose to introduce a manageable number of eco-innovation tools into a standard one-semester design course in process engineering with particular focus on the identification of eco-problems in existing technologies, selection of the appropriate new process intensification technologies (knowledge-based engineering), and systematic ideation and problem solving (knowledge-based innovation and invention).

Tools for Eco-Innovation

The proposed eco-innovation tools, their application field and workload in teaching are presented in Table 1 and discussed in this section. Educators can apply one or several tools for their courses depending time availability and on the competencies and skills to be learned or improved, using their own examples or problems. The explanation efforts of educators are considered as low – if a tool requires up to 10 minutes introduction and its application is almost self-explanatory. The medium efforts correspond to 30 minutes introduction with examples and high efforts correspond as a rule to a two hour introductory seminar in which the educator has to guide students in each step of the learning process.

Table 1: Eco-innovation tools for integration into the process engineering subjects

N	Eco-innovation tool	Application field (skills)	Explanation efforts of educator
1	Identification of eco-engineering contradictions	Problem definition and analysis	medium
2	Process mapping incl. resources analysis		high
3	Ecological Anticipatory Failure Identification	Problem definition and analysis, engineering creativity	low
4	Process Intensification technologies (database)	Knowledge-based engineering	medium
5	Nine fields heuristic MATCHEM-IBD	Engineering creativity, knowledge-based innovation and invention	low
6	Five cross industry analogies		low
7	TRIZ Inventive operators		medium

Identification of eco-engineering contradictions

Economic growth and ecological problems motivate industries to apply eco-friendly technologies and equipment. At the same time, the major negative implication of the technological progress in process engineering is attributable to its environmental impact. For example, our analysis of 150 patents describing process technologies involving handling of solids (granulates, powders etc.) has encountered 131 inventions with possible negative environmental side effects. Moreover, even if the inventions propose eco-friendly products or processes, additional environmental problems can still appear in the obtained solutions. A situation in which the improvement of one parameter (e.g. productivity) implies a worsening of another parameter (e.g. energy consumption) is defined as an engineering contradiction (VDI, 2016). Identification of engineering contradictions is one of the important outcomes of the problem definition in eco-design (Russo, 2015). In this context, two types of eco-engineering contradictions can be defined in process engineering: primary contradiction and secondary contradiction. A primary eco-engineering contradiction occurs when the improvement of a non-ecological engineering parameter (e.g. productivity) leads to a deterioration of an environmental characteristic in process or equipment (e.g. air pollution), or vice versa. Consequently, a secondary eco-engineering contradiction is a situation where the improvement of one ecological parameter causes the worsening of another ecological parameter. The awareness of eco-contradictions as well as the ability to identify or at least to guess them belongs to the major competences in eco-innovation. Especially the secondary eco-contradictions are not always evident for the students and engineers applying new technologies. The secondary contradictions can be identified with a tool “Correlation matrix of eco-requirements”, proposed by the authors in the previous research (Livotov et al., 2019). A fragment of the correlation matrix with 12 environmental parameters is presented in Figure 1, where “-1” indicates a possible secondary eco-contradiction, “+1” outlines a positive synergetic effect and “0” – a neutral or unknown counteraction between two eco-parameters. This correlation matrix is based on the analysis of 200 patents and 155 process intensification technologies. It supports students and engineers to see how one improved eco-parameter can affect the other eco-parameters either positively or negatively. For example, the reduction of Acidification (7) can negatively affect Energy consumption (1), Safety risks (4), Depletion of abiotic resources (6) and Toxicity (7).

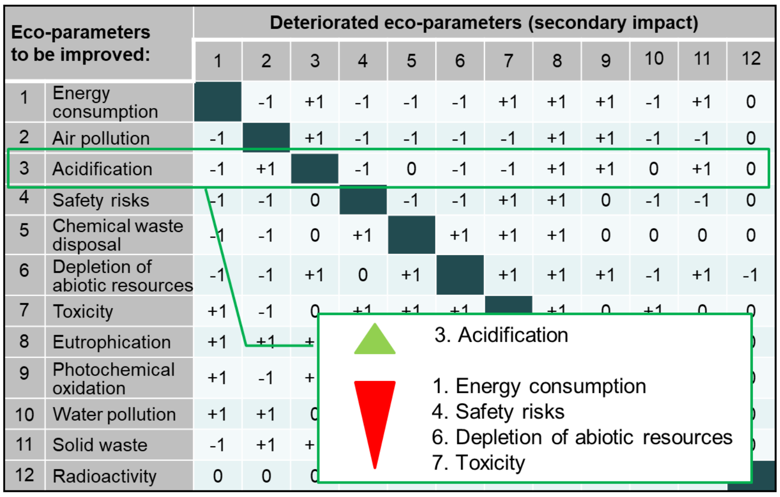

Figure 1: Correlation matrix of eco-requirements (fragment)

The presented 12x12 matrix can be proposed also with a larger number of individual eco-requirements, giving more precise recommendations for possible secondary eco-engineering contradictions. The identification of these requirements for a specific technology or process step can be performed with the help of the Process Mapping method.

Process mapping and resources analysis

Process mapping is an easy-to-use technique to systematically identify eco-problems and innovation tasks in each process step and in the production process as a whole (Casner, 2017). The method includes the capturing and analysis for each process of the information on process equipment, processing methods, input/output and quality parameters, product, available resources, and environment. It results in the formulation of innovation tasks and intensification opportunities of the technologies and equipment in each process step and in the whole production process. Process mapping delivers reliable results for existing technologies or well-known processes. Therefore, it can be easily integrated into existing subjects in full or partially, for example, by presenting new technologies using the logic of process mapping as illustrated in Table 2.

An important role in understanding and creative solving eco-innovation problems belongs to the analysis resources available in the system and environment. The TRIZ methodology offers a self-explanatory checklist with examples for identification and mobilisation of resources (Livotov & Petrov, 2013). For instance, the resources checklist includes a comprehensive listing of possible substance states and properties, physical and technical fields and energies, easily available substances, forces or energies, modifications and alteration of substances and energies etc.

Table 2: Process mapping technique

Methodical step	Content (subject for analysis or definition)
1. Equipment	• Positive main functions and auxiliary functions • Missing functions, negative functions, undesired properties
2. Processing methods	• Positive effects • Negative effects, undesired properties
3. I/O and quality parameters	• Target values, ideal values • Controllability of parameter, accuracy of process analysis
4. Product	• Product flow, physical state, energy state • Reactions and transformations • Useful and undesired properties
5. Available resources	• Substances, material flows • Fields, energy flows, time, space, information
6. Surrounding and environment	• Resources (substances, energy etc.) • Positive and negative effects, undesired properties
7. Eco-innovation tasks	Eco-contradictions and definition of eco-problems: • enhancing positive functions and effects • eliminating negative functions, effects, undesired properties

Ecological Anticipatory Failure Identification

The method of Anticipatory Failure Identification, AFI for short, known in TRIZ (VDI, 2016) can be adapted for eco-innovation problems to predict possible or hidden sources of potential environmental impact especially if knowledge and experience with technologies are lacking. AFI is both a systematic and creative method. Instead of defensively asking “What eco-problems can be expected in a system?” one inverts the task formulation offensively to “Find or invent means which definitely cause a negative environmental impact”. For this reason, the AFI method is also called the “subversive” failure analysis. In our experience the AFI-method can be easily integrated into the process engineering courses as a 30 minutes creative exercise with the following steps:”

1. Formulate the inverted task: “Create a negative environmental effect in a system”;
2. Identify all resources of the system and surroundings such as substances, energy etc.;
3. Mobilize and transform creatively the resources to produce environmental harm;
4. Generate ideas to prevent eco-problems “invented” in the previous step.

Process Intensification as knowledge based environmental engineering

According to Boodhoo and Harvey (2013), Process Intensification (PI) is a knowledge-based methodology leading to more efficient processes, equipment and plant design, characterised by reduced energy consumption and losses, raw material and cost reduction, higher process quality, safety and better environmental performance. The PI technological databases are continuously developing and currently cover a wide range of more than 155 processing methods and equipment, such as operations involving and not-involving chemical reactions, hybrid separation methods, multifunctional reactors, alternative energy sources and others (Wang et al., 2017). The work with the PI database can be naturally integrated in any design course in process engineering and supported by the “Intensified by Design (IbD)” Freemium Internet platform – a knowledge-based engineering system for the intensification of processes involving solids handling, co-developed by the authors within a consortium of 22 organisations (research institutes, universities, industrial manufacturers and SMEs) led by IRIS in Barcelona and funded by the European Commission under the Horizon 2020 SPIRE programme (IbD, 2018; Law et al, 2017). The IbD database of PI technologies enables students to identify and shortlist the intensified equipment types, methods and applications faster in accordance with the objectives and constraints of their tasks. For example, a request for energy saving distillation with high potential to reduce CO_2 emission leads among others to the following technologies: heat-integrated distillation, reactive distillation and membrane-assisted reactive distillation. Table 3 illustrates examples of two PI-technologies with better environmental performance which were selected and implemented in the case studies of the IbD-Project (IbD, 2018).

Table 3: Application of the PI database for eco-innovation in process engineering (examples)

PI Technology	Process	Technological outcomes	Environmental outcomes
1. Coanda elbow-jet air classifier	Metallic powder classification	Increased process yield; reduced maintenance costs	Lower the risk of exposure to carcinogenic powders
2. Swirling fluidized bed reactor	Separation and drying	Reduced equipment size and maintenance costs	Reduced energy consumption.

Inventive operators and thinking heuristics

The fact that thinking heuristics, inventive principles and operators support engineering creativity has been evidenced in numerous reports from industry and academia. The TRIZ methodology with its basic principles of Ideality (Ideal or Ultimate Final Result) and of the compromise-free problem-solving fit in perfectly with the strategy of sustainable eco-innovation. On the other hand, TRIZ helps to mobilize resources of the existing processes and to reduce the negative environmental impact of technologies without efficiency losses. Therefore, three TRIZ-based heuristics are recommended here for enhancing engineering creativity of the students: Operator MATCEM-IBD, five cross-industry analogies, and 22 inventive operators, selected from 40 TRIZ Inventive Principles.

The Operator MATCEM-IBD, being a part of the TRIZ Substance-Field analysis (VDI, 2016), triggers the engineering creativity and motivates students to search for possible solution ideas based on nine different fields or principles of operation: Mechanical, Acoustic, Thermal, Chemical, Electric, Magnetic, Intermolecular, Biological and Data processing (MATCEM-IBD). Its efficiency has been proven by numerous internationally conducted experiments. (Belski, 2016). Within 20 minutes the students could considerably increase the quantity and variety of feasible solution ideas for an open-ended problem.

Another simple ideation technique, the five cross-industry analogies, helps to obtain at least a 2.5-fold growth in the ideation yield and to increase breadth of ideas in a 25 minutes ideation session in comparison with a control group (Livotov, 2018). Five heuristics are using the creative thinking in analogies, TRIZ methods of Feature Transfer and Function-Oriented Search, and the TRIZ operator Size-Time-Costs:

1. How is a similar problem solved in technical domains or fields similar to yours?
2. How is a similar useful function realised in other technical domains?
3. How is a similar negative effect counteracted in other technical domains?
4. How is a similar problem solved in other domains on the micro- and macro-level?
5. How is a similar problem solved in the nature (plants, insects, animals, humans)?

The 40 Inventive Principles, as one of the most widely used TRIZ tools, has been extended by the authors with more than 60 additional sub-principles for the process engineering problems. In the next step, a comprehensive analysis of eco-patents, PI operations and methods, and of the scientific literature in the field of eco-innovation presented in (Livotov, 2019), allowed one to select from 40 TRIZ inventive principles (with in total 160 sub-principles) the 15 statistically strongest inventive principles with the corresponding 22 sub-principles for environmental problems in process engineering:

- 35 Transform physical and chemical properties (sub-principles: 35d, 35a, 35b)
- 02 Leaving out / Trimming (sub-principles: 2a, 2e)
- 05 Combining (sub-principles: 5b, 5a)
- 25 Self-service / Use of resources (sub-principles: 25b, 25a)
- 29 Pneumatic or hydraulic constructions (sub-principles: 29e, 29a)
- 28 Replace mechanical working principle (sub-principle: 28a)
- 15 Dynamism and adaptability (sub-principle: 15a)
- 22 Converting harm into benefit (sub-principle: 22a)
- 10 Prior useful action (sub-principle: 10a)
- 09 Prior counteraction of harm (sub-principles: 9a, 9b)
- 01 Segmentation (sub-principle: 1a)
- 34 Rejecting and regenerating parts (sub-principle: 34a)
- 36 Phase transitions (sub-principle: 36a)
- 20 Continuity of useful action (sub-principle: 20a)
- 40 Composite materials (sub-principle: 40a)

The efficiency of the selected inventive principles for eco-innovation in process engineering is the subject of on-going research.

Concluding Remarks and Outlook

There is a scientific and practical demand to structure the existing and continuously growing body of knowledge in the field of eco-innovation, including best practices, examples of case studies, etc. The proposed educational approach equips students with the advanced knowledge, skills and competences in the field of eco-innovation. Analysis of the student's work allows one to recommend simple-to-use tools for a fast application in process engineering, such as process mapping, database of eco-friendly process intensification technologies, and up to 20 strongest inventive operators for solving of environmental problems. For many students in the survey, even the small workload has strengthened their self-confidence and skills in eco-innovation. The structured education in eco-innovation can be successfully integrated in a one semester course of process engineering design. The future research should be focused on further development of learning resources, such as standard guidelines, interdisciplinary examples, best-practice recommendations, and in particular on optimization and computerization of the educational eco-innovation toolbox. Even if the proposed approach is limited to the domain of process engineering, its basic principles and tools can be suggested for the other domains of eco-innovation.

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