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Eco-Innovation in Process Engineering: Contradictions, Inventive Principles and Methods

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Abstract. Economic growth and ecological problems motivate industries to apply eco-friendly technologies and equipment. However, environmental impact, followed by energy and material consumption still remain the main negative implications of the technological progress in process engineering. Based on extensive patent analysis, this paper assigns more than 250 identified eco-innovation problems and requirements to 14 general eco-categories with energy consumption and losses, air pollution, and acidification as top issues. It defines primary eco-engineering contradictions, in case eco-problems appear as negative side effects of the new technologies, and secondary eco-engineering contradictions, if eco-friendly solutions have new environmental drawbacks. The study conceptualizes a correlation matrix between the eco-requirements for prediction of typical eco-contradictions on example of processes involving solids handling. Finally, it summarizes major eco-innovation approaches including Process Intensification in process engineering, and chronologically reviews 66 papers on eco-innovation adapting TRIZ methodology. Based on analysis of 100 eco-patents, 58 process intensification technologies, and literature, the study identifies 20 universal TRIZ inventive principles and sub-principles that have a higher value for environmental innovation. The presented research work belongs to the European project "Intensified by Design platform for the intensification of processes involving solids handling" (IbD, http://ibd-project.eu), funded by the European Commission under the Horizon 2020 SPIRE programme.

Keywords: Eco-engineering contradictions, Eco-innovation, Process engineering, Process intensification, TRIZ.

1 Introduction

1.1 Definition of Eco-Engineering Contradictions

The rapid industrial growth and technological progress of the recent decades created many environmental concerns. As a result, industrial companies become more environmentally responsible, trying to reduce negative ecological impact and potential risks, and to apply new eco-friendly technologies. However, implementation of new technologies in process engineering often lead to additional environmental problems, resulting in engineering contradictions [1]. The engineering contradiction is defined as a situation in which the improvement of one parameter (e.g. productivity) implies a deterioration of other parameters (e.g. energy or water consumption) within a system.

Moreover, businesses often choose short to middle-term economic benefits of traditional technologies instead of sustainable and environmental-friendly innovations with economic advantages in the long term only. Applying or developing eco-friendly technologies may be a great challenge for non-green companies because it often requires the acquisition of new resources and competences [2]. Therefore, new technologies in process engineering still demand innovative efforts to reduce environmental issues while increasing economic and technical benefits.

However, even if inventions and new solutions propose an eco-friendly product design or process, additional environmental problems still can appear as negative side effects of obtained solutions, creating a *secondary* eco-engineering contradiction. The secondary eco-engineering contradiction is a situation where the improvement of ecological parameter causes the worsening of another environmental parameter of a technical system, process, or product.

For example, the invention WO2013165633A1 describes a method to enhance bulk handling properties of pigmentary powder titanium dioxides (TiO_2). The method increases the bulk density by utilizing ammonia, improves the powder properties, reduces dust formation and waste water disposal. However, the analysis of the proposed solution reveals another eco-problem such as ammonia gas generation which requires specific operations handling safety, accident prevention and environmental care. In another example, the environmentally-friendly method for preparing ceramic powders disclosed in US8765261B2 decreases the amount of carbon waste but generates dust and requires additional measures to prevent air pollution. Thus, two types of eco-engineering contradictions - primary and secondary - can be defined in process engineering or other engineering domains, as shown in Table 1. Further examples of eco-engineering contradictions in process engineering are presented in Table 2.

Table 1. Types of eco-engineering contradictions.

Type of contradiction	Problem situation	Description of contradiction
1. Primary eco-contradiction	a) technological innovation leads to environmental problems b) eco-friendly technology causes additional costs or worsening of technical parameters	a) improvement of non-eco parameter causes worsening of eco-parameter b) improvement of eco-parameter causes worsening of non-eco parameter
2. Secondary eco-contradiction	Eco-friendly technology causes additional negative environmental impact	improvement of one eco-parameter causes worsening of another eco-parameter

The eco-contradictions are not always evident for the engineers applying new technologies. For example, a support tool for contradiction identification “Contradiction Prompter” is proposed in [3]. As primary eco-contradictions are already the focus of attention in industry and society, the secondary eco-contradictions are not systematically analyzed. Therefore, the presented paper has an emphasis on early identification and resolving of secondary eco-contradictions to enable a smooth implementation of new eco-friendly technologies.

Table 2. Examples of primary (PC) and secondary (SC) eco-engineering contradictions.

	Invention	Ecological advantages	Negative side effects
1.	Process of paint sludge recycling US20140303267A1	+ Decreases chemical waste disposal in the paint sludge	- Requires treatment of gases and vapors which contain hazardous chemical compounds (SC)
2.	Method and apparatus of continuous recovery of (meth)acrylic acid (US20150203431A1)	+ Reduces energy consumption in the distilling process of acid	- Higher loss of (meth)acrylic acid in the distillation process (SC) - Increased amount of waste water (SC)
3.	Method and system for reheating flue gas using waste heat to maintain dry chimney stack operation (US20160169510A1)	+ Decreases energy consumption + Minimizes SO_2 emission	- Causes corrosion of the hot side heat exchanger (PC)
4.	Counter circulating liquid processing system by repeatedly re-using thermal energy (US2017355617A1)	+ Reduces energy consumption in thermal distillation of sea water + Increase heat exchange devices efficiency	- Longer process duration since the apparatus has multiple stages (PC)

1.2 TRIZ Methodology

TRIZ is the internationally acknowledged Russian abbreviation for the Theory of Inventive Problem Solving. The classical TRIZ developed by the Russian scientist G.S. Altshuller (first publication in 1956) and his co-workers [4] has been significantly supplemented in the last two decades [5]. Today TRIZ is considered as one of the most comprehensive, systematically organized invention knowledge and creative thinking methodologies [6]. TRIZ delivers scientifically founded and structured approach to forecasting evolution of engineering systems and includes numerous tools and methods for product and process innovation. For example, the TRIZ Standard of the Association of German Engineers VDI 4521 (2016) [7] contains 25 TRIZ tools for definition of innovation objectives, problem formulation, idea generation and evaluation.

In contrast to the common creativity techniques, only TRIZ relies on the unbiassed laws of evolution of technical systems and enables noticeable increase of creative and inventive productivity. The discovery and structuring of these laws and other TRIZ components have been the result of the study and analysis of globally available patents over a period of several decades. One of the main advantages of TRIZ is that it allows to find new inventive solutions for a given problem in a systematic way by using the entire potential of science and engineering, also outside of the field of originally formulated problem.

Besides the central concept of the laws of engineering systems evolution, the identification and uncompromised elimination of engineering contradictions in technical systems, the concepts of Ideality and Ideal Final Result, and the comprehensive mobilization of available resources belong to the fundamentals of TRIZ. Among the most important TRIZ components are

1. 40 inventive principles for eliminating engineering contradictions and system of their application in form of the contradictions matrix (39x39 Altshuller matrix with 39 technical parameters for definition of engineering contradictions).
2. Substance-field analysis and 76 standard solutions for solving technical problems.
3. Step-by-step algorithms for inventive problem solving (abbr.: ARIZ) as a universal tool for solving difficult problems and comprehensive search for solutions.
4. Separation principles for eliminating physical contradictions, i.e. in a situation where one system component should have opposite properties, for example liquid and solid.
5. Resource analysis for analyzing and mobilization of system resources such as time, space, substances, fields (energy), information and functions.
6. Database of physical, chemical, geometrical and other effects and their technical applications.
7. Anticipatory failure identification for analysis and prediction of possible sources of failures.
8. Evolution patterns or trends to forecast the development of technical systems.
9. Creativity enhancing methods, such as operator Size -Time-Cost, "Little people" models, and others.
10. System operator (multi-screen analysis) and function analysis.

In the last two decades, Computer-Aided Innovation tools and new analytical methods for comprehensive problem formulation and contradictions identification have been continuously developed in addition to the classical TRIZ problem-solving tools such as cause-effect-chains analysis and root-conflict analysis [7], problem graph [8], network of contradictions and other TRIZ-related methods, reviewed in [9].

Practically, all these TRIZ tools can be used for solving different tasks and problems of eco-innovation. However, one universal ideation tool appears to be more convenient and favorable for the practical work. For this purpose, the classical 40 Inventive Principles including 88 sub-principles [4] have been extended by additional 72 sub-principles extracted from TRIZ standard solutions, evolution patterns and other inventive operators relevant for process engineering. This enhanced version of 40 inventive principles with 160 sub-principles is used in the presented research and displayed in the Appendix.

In comparison with systematic eco-design tools and green innovation guidelines to assess and overcome negative environmental impacts, only TRIZ offers the methods and tools for identification and elimination of engineering contradictions and helps dramatically enhance the inventive skills of engineers. Therefore, many researches proposed to adapt TRIZ for the domain of eco-innovation in the chemical industry [10], for environment-friendly cleaner manufacturing [11], design of green products [12] or eco-design [13].

For example, the authors of [14] adapt the classical TRIZ contradiction matrix with 39x39 engineering parameters to a 14x14 matrix to resolve contradictions in process engineering with a set of 8 solution principles. In this matrix 3 of 14 parameters, such as *Environmental impact*, *Hazardous nature*, and *Process safety* can be applied for formulation of 17 primary and 4 secondary eco-engineering contradictions. Another research paper presents a matrix with 6 eco-goals and 21 functional parameters and identifies 63 primary eco-contradictions in 80 patents and 50 products [15]. It shows that eco-contradictions are caused most frequently by the increased energy consumption in new products or processes. The authors of the eco-ideation tool for reduction of greenhouse gas emissions [16] attest TRIZ an important role in eco-innovation.

In this paper 66 eco-innovation methods using elements of TRIZ are briefly reviewed to identify TRIZ tools most frequently applied to environmental problems and in the eco-design approaches. Additionally, the performed patent analysis in the field of eco-innovation and process engineering attempts to identify the typical eco-engineering contradictions with the corresponding strongest TRIZ inventive principles for solving environmental problems, and thus to enhance existing eco-innovation tools.

The presented research work is a part of the European project "Intensified by Design (IbD) platform for the intensification of processes involving solids handling" 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 [17]. As the IbD project is dealing with processes including pharmaceuticals, ceramics and chemical reactions in the presence of solids, a significant part of performed patent analyses is related to solids handling.

2 Eco-Problems and Inventive Principles in Patent Literature

2.1 Patent Analysis

The growing importance of patent literature as a source of actual technical information is outlined in numerous scientific works and applications [18, 19, 20]. Numerous studies have shown that, depending on the year and the technical domain, 70–90% of the technical information can be found only in patent documents [20]. Patent documents in the field of process engineering disclose problems and corresponding solutions also regarding environmental issues [1, 19]. Thus, selecting and analyzing patents in the field of eco-innovation and process engineering, allows one to systematically extract and to classify environmental requirements and problems addressed by the inventions. On this basis typical eco-engineering contradictions can be identified and used to predict potential secondary eco-problems of new environmentally friendly technologies.

For this purpose, 200 international patent documents with the application date between 2000 and 2017 in the field of process engineering have been analyzed. The patent documents were retrieved by using online search engines and databases of the German Patent and Trade Mark Office (DPMA), the European Patent Office (EPO), and of the

United States Patent and Trademark Office (USPTO). 150 of the analyzed documents (patents or patent applications) belong to the field of process intensification in the pharmaceutical (50 documents) and ceramic (100 documents) powders processing. Among these 150 solids handling patents, 50 inventions deal with different environmental aspects such as water and energy consumption, air pollution and chemical waste disposal, etc. In addition to the 150 solids handling patents, 50 documents with eco-friendly technologies were retrieved from other domains of process engineering dealing with operations both involving and not involving chemical reactions. The general procedure of the performed patent analysis included the following main steps:

1. Identification of documents with eco-relevant problems or goals of invention.
2. Categorization of the initial problems and their translation to a list of solution-neutral eco-requirements, such as *reduce air pollution with dust* etc.
3. Extraction of main solution principles as listed in the patent claims and description and their assignment of the corresponding 40 TRIZ inventive principles.
4. Documentation of ecological advantages of the invention by full-text analysis.
5. Identification of ecological disadvantages and other secondary problems of the invention by patent citations according to the method described in [19].
6. Identification of eco-engineering contradictions between the advantages and the secondary problems of inventions.

2.2 Identification of Environmental Problems in Patent Documents

The analysis of 100 full-text patent documents solving environmental problems (50 documents related to processes involving solids handling and 50 documents related to other eco-issues in process engineering) has identified 252 ecological requirements or problems: 137 requirements in 50 solids handling patents and 115 requirements in 50 patents related to other eco-issues, as exemplarily presented in Table 3. Depending on the detail level, these ecological requirements and eco-problems can be combined in various groups or categories. A general categorization using 14 environmental impact categories is shown in Table 4. This categorization was proposed according to the international Life Cycle Assessment (LCA) norms ISO 14040:2006, ISO 14044:2006 and Guidelines for Incorporating Eco-Design ISO 14006:2011. It also takes into consideration the 13 criteria of the Process Design for Sustainability (PDfS) and other environmental metrics, summarized in [21].

Table 3. Ecological requirements identified in 100 patents (fragment).

No.	Solution-neutral eco-requirements	Category	Patent No.
1.	Reduce formation of effluent water in the coal gasification process	Water pollution	US 9505999 B1
2.	Reduce dust formation in granulation process of titania slag	Air pollution	WO 2014096541A1
3.	Eliminate chemical agents from recycled paint sludge	Chemical waste disposal	US 20140303267A1
…	…	…	…
252.	Reduce contamination of breathing air with powder while filling containers	Safety risks; Air pollution	WO 2013044921A2

In such classification one ecologically critical agent or substance can be simultaneously assigned to various categories. For instance, ammonia (NH_3) not only causes eutrophication (cat. 8), but it also has further problems such as acidification, toxicity and photochemical oxidation (cat. 3, 7, 9 respectively).

Interestingly, thermal process technologies and equipment are responsible for the major eco-problem category *Energy consumption*, which was mentioned in total 50 times in 100 eco-patents: 38 times as an invention task and 12 times as a negative side effect.

Table 4. Categories and number of eco-problems mentioned in 100 eco-patents.

No	Category	Description	Number
1	Energy consumption	High amount of energy used in chemical processes (e.g. thermal distillation), large amount of energy wasted as heat	50
2	Air pollution	Fly ash generation, particulate matters formation (dust, smog), global warming (greenhouse gas emissions)	45
3	Acidification	Acidic gases emissions (SO_2 & CO_2), acid rain emissions (H_2SO_4 & HNO_3), NH_3 and NO_X emissions	26
4	Safety risks	Flammability risk, high pressure and temperature, vapor cloud explosion	21
5	Chemical waste disposal	Chemical hazardous waste disposal (organic peroxides, flammable gases, corrosive substances)	20
6	Depletion of abiotic resources	Land, water, air depletion	20
7	Toxicity	Human toxicity, hazardous chemical waste (ammonia, phosphates, fragrance chemicals), eco toxicity (fresh water, marine and land toxicity)	19
8	Eutrophication	Degradable organic substances and surplus nitrogen e.g. NO_3-, NO_X and NH_3 emissions	15
9	Photochemical oxidation	NO, CO, SO_2 and ammonium emissions	12
10	Water pollution	Groundwater pollution, thermal pollution, pollution with chemicals such as hazardous chemical agents and solvents disposal	11
11	Solid Waste	Saturated waste limestone powder, concentrated sludge	5
12	Radioactivity	Radioactive materials leakage	4
13	Ozone layer depletion	Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) emissions to atmosphere	3
14	Raw material intensity	High raw material usage	1

The separate evaluation of eco-problems frequency in 50 eco-patents dealing with ceramic and pharmaceutical powders processing and in 50 eco-patents in process engineering dealing with operations involving and not involving chemical reactions is presented in Fig. 1. The categories 1. *Energy consumption* and 2. *Air pollution* are the most frequently mentioned as primary or secondary problems in the analyzed patent literature. On the other hand, category 3. *Acidification* rarely appears in solids handling patents, this contrasting with the patents related to eco-problems in process engineering.

The 14 environmental categories allow one to check in detail the possible ecological impact of new technologies and equipment and to formulate resulting eco-engineering contradictions. The presented results can be refined if the level of detailing for eco-categories is changed to a higher number of individual categories. Once determined, the identified ecological advantages and disadvantages of inventions allow one to zoom dynamically into a problem situation with required resolution and to identify the root causes of the occurring eco-problems.

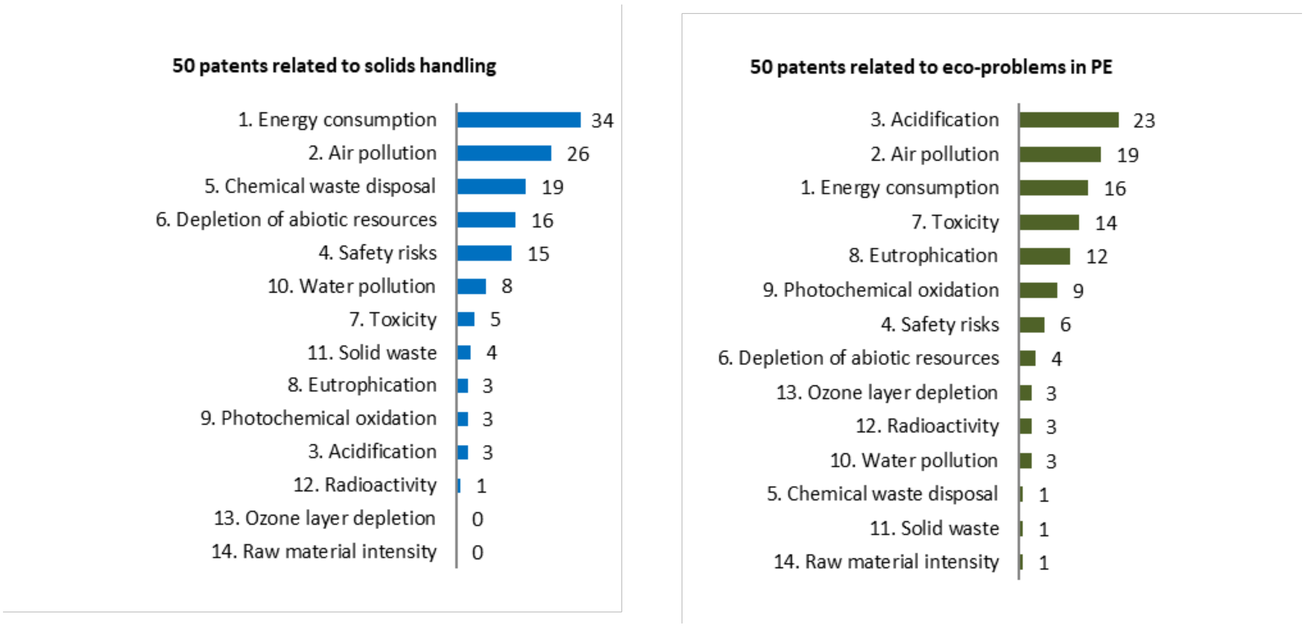

Fig. 1. Eco-problems mentioned in solids handling and other process engineering (PE) patents (based on the analysis of 100 eco-patents; multiple assignment).

The performed analysis of 150 patent documents in the field of pharmaceutical (50 documents) and ceramic (100 documents) powders processing gave an opportunity to identify 208 typical invention tasks and requirements of process intensification (PI) involving solids handling. These identified demands represent economic, technical and environmental aspects, such as, for example, increase productivity, avoid agglomeration of powder, enhance mechanical stability of granules, avoid fouling and clogging, minimize labour-consuming maintenance, and others. Like the evaluation of eco-patents presented above, these 208 requirements can be assigned to a lower number of process intensification categories for solids handling.

The following 27 categories have been proposed by the authors in [19]: Productivity, Investment costs, Solids handling efforts, Process duration, Production capacity, Size of equipment, Complexity, Controllability, Reliability, Adaptability of equipment, Replaceability of equipment, Maintenance and cleaning, Quality of product, Mechanical properties, Chemical properties, Physical properties, Uniformity, Disintegration, Agglomeration, Moisture content, Product composition, Homogeneity, Energy consumption, Water consumption, Process efficiency, and Environmental performance.

Due to the patent analysis it is possible to compare the number of inventive tasks and advances with the quantity of secondary problems in each category. The Figure 2 shows the top five categories with the highest number of secondary problems in 150 solids handling patents. The important finding of this study is that the most frequent secondary side effects encountered in the inventions are of an ecological nature, these being the negative environmental impact (131 times), higher water or material consumption (65 times), and higher energy consumption (57 times). On the other hand, the inventive goals in the patent literature are mainly related to the quality parameters of the product and its mechanical, physical and chemical properties.

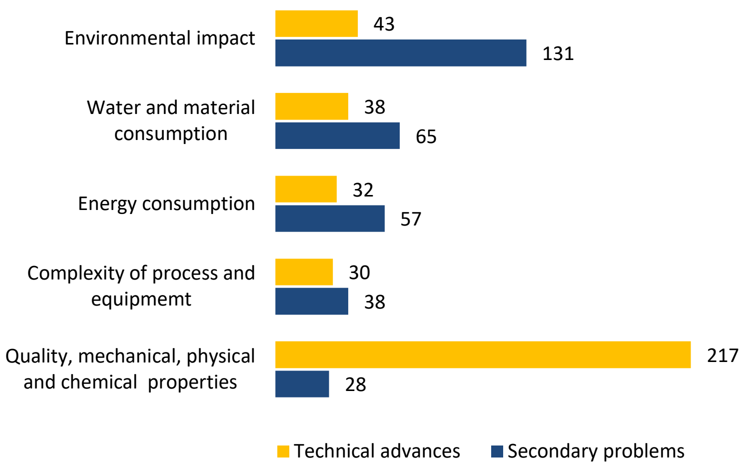

Fig. 2. Technical advances and initial problems solved by the inventions and new secondary problems (disadvantages), identified from 150 solids handling patents (number of mentioning, multiple assignment).

Such a situation leads inevitably to numerous primary eco-engineering contradictions in solids processing between environmental categories (environmental impact, energy and material consumption) and other economic and technical categories (cost, quality of product, complexity of process and equipment etc.). A correlation matrix 27x27 build with 27 process intensification categories relating to solids handling mentioned above is presented in [19]. This matrix presents 215 primary eco-contradictions identified in the 150 solids handling patents.

2.3 Identification of Environmental Problems in Case Studies

To verify the findings from the patent analysis, the environmental problems of existing technologies, dealing with continuous drying process in pharmaceutical tablet manufacturing and granulation process in ceramic industry, have been identified using the process mapping method.

Process mapping [22] is an easy-to-use technique to identify innovation tasks and solution-neutral process intensification requirements in existing processes. The method involves breaking down of a complete industrial production process into process steps to capture in each step the information on process equipment, processing methods, input/output quality parameters, product, available resources, and environment, as in detail presented in Figure 3. Process mapping results in comprehensively capturing and ranking of all existing problems, formulated as enhancement of positive functions or effects, elimination of negative functions, effects or undesired properties, raising degree of controllability, accuracy, and automation of the process step.

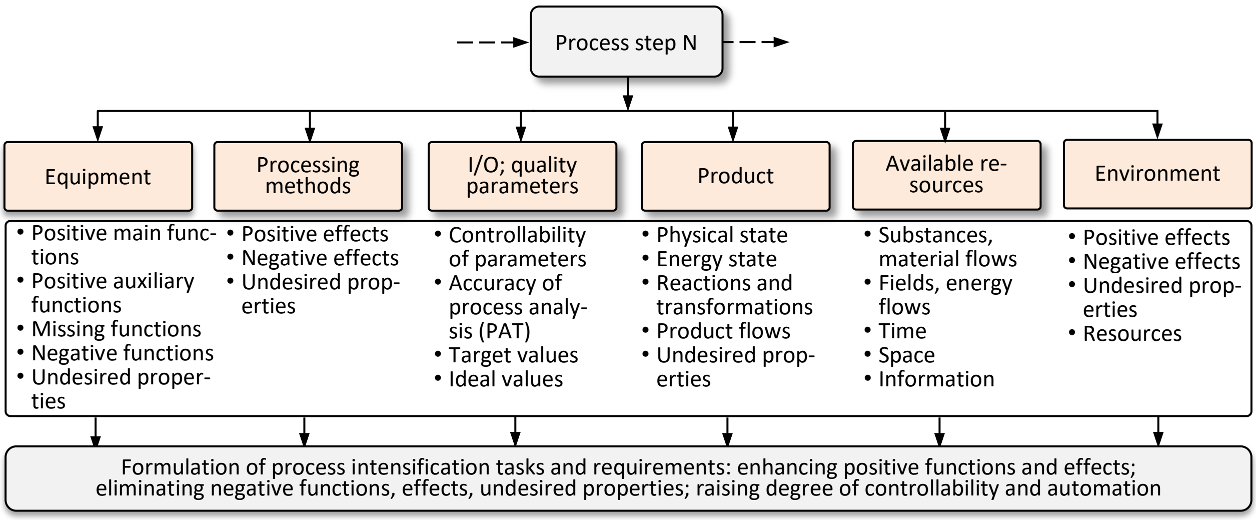

Fig. 3. Process mapping technique: fragment, adapted from [22].

The results of the pharmaceutical and ceramic powder processing case studies examined in the IbD HORIZON 2020 project [17] are briefly presented in Table 5. In both case studies 22 environmental problems constitute 29% of all problems. Eco-problems related to the Energy consumption category are in the first place with 36%, followed by the Air pollution (32%), Water pollution and consumption (23%), and Raw material losses (9%). These analyses show a good correlation between the occurrences of environmental problems in the case studies and in the evaluated eco-patents (see Table 4).

Table 5. Identification of environmental problems in case studies.

Case study	Problems	Environmental problems				
	Total amount	Energy consumption	Air pollution	Water pollution, consumption	Raw material losses	Total
1. Continuous drying process in pharmaceutical industry	32	3	2	2	-	7
2. Granulation process in ceramic industry	45	5	5	3	2	15
Total amount of problems	77	8	7	5	2	22

2.4 Correlation Matrix of Eco-Requirements

As reported above, the identification of the secondary eco-engineering contradictions between different environmental parameters required a more detailed analysis of the 100 patent documents with ecological goals of inventions, which were assigned to 14 environmental categories. The obtained information about existing correlations between the initial eco-problems to be solved by the inventions and the corresponding secondary eco-problems can be used to build a correlation matrix predicting secondary eco-contradictions in the field of analysis. Contrary to the deterministic definition of contradictions used in the classical TRIZ, the identified contradictions are expected here with a certain degree of probability. A fragment of correlation matrix with 14 environmental categories is presented in Table 6, where "-1" indicates a possible negative impact and thus a secondary eco-contradiction, "+1" indicates a positive impact, and "0" – a neutral or unknown counteraction between two eco-categories. In other words, the correlation matrix helps engineers to see how one improved eco-parameter can affect the other eco-parameters either positively or negatively. For example, reduction of *Toxicity* (7) has positive impact on *Water pollution* (10) but can negatively affect *Air pollution* (2), for example, by use of sorbents. The matrix displays 35 secondary eco-contradictions, which can be resolved by TRIZ inventive principles.

As mentioned in section 2.2, the presented 14x14 correlation matrix can be dynamically displayed with higher resolution up to 252x252 individual eco-requirements, giving more precise recommendations for possible secondary eco-engineering contradictions. Such a dynamic correlation matrix based on patent analysis can combine various levels of abstractions or generalization and increase the accuracy and reliability of ecological impact assessments for new technologies.

Table 6. Correlation matrix with identified environmental problems and secondary eco-contradictions: “-1” negative impact (eco-contradiction); “+1” positive impact; “0” – neutral

Eco-parameters to be improved:		Eco-parameter changed for the worse (secondary impact):											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	*Energy consumption*		-1	+1	-1	-1	-1	+1	+1	+1	-1	+1	0
2	*Air pollution*	-1		+1	-1	-1	-1	-1	+1	+1	-1	-1	0
3	*Acidification*	-1	+1		-1	0	-1	-1	+1	+1	0	+1	0
4	*Safety risks*	-1	-1	0		-1	-1	+1	+1	0	-1	-1	0
5	*Chemical waste disposal*	-1	-1	0	+1		+1	+1	+1	0	0	0	0
6	*Depletion of abiotic resources*	-1	-1	+1	0	+1		+1	+1	+1	-1	+1	-1
7	*Toxicity*	+1	-1	0	+1	+1	+1		+1	0	+1	0	0
8	*Eutrophication*	+1	+1	+1	+1	+1	+1	+1		+1	0	0	0
9	*Photochemical oxidation*	+1	-1	+1	0	-1	-1	0	+1		0	0	0
10	*Water pollution*	+1	+1	0	0	0	+1	+1	0	0		0	0
11	*Solid Waste*	-1	+1	+1	+1	-1	+1	0	0	0	-1		0
12	*Radioactivity*	0	0	0	0	0	0	0	0	0	0	0	
13	*Ozone layer depletion*	0	0	0	0	0	0	0	0	0	0	0	0
14	*Raw material intensity*	0	0	0	0	0	0	0	0	0	0	0	0

2.5 TRIZ Inventive Principles extracted from Eco-Patents

Identification of TRIZ inventive principles used in 100 patent documents dealing with ecological problems in the field of process engineering was a part of this study. The top 10 inventive principles and sub-principles most frequently used in the analyzed patent literature to solve eco-problems are presented in Fig. 4. There is a significant difference between the top 10 principles for eco-problems and the top 10 principles encountered in the 155 process intensification technologies (N14, 29, 35, 2, 5, 36, 6, 28, 24, 18) [23] with only 3 similar principles N29, 35 and 3. Also a comparison of the top 10 principles for eco-problems (Fig. 4) with the statistically strongest and most often applicable inventive principles [24] (N35, 10, 1, 28, 2, 15, 19, 3, 17, 13 – see appendix) outlines only 4 similar principles N 35, 1, 2, 15.

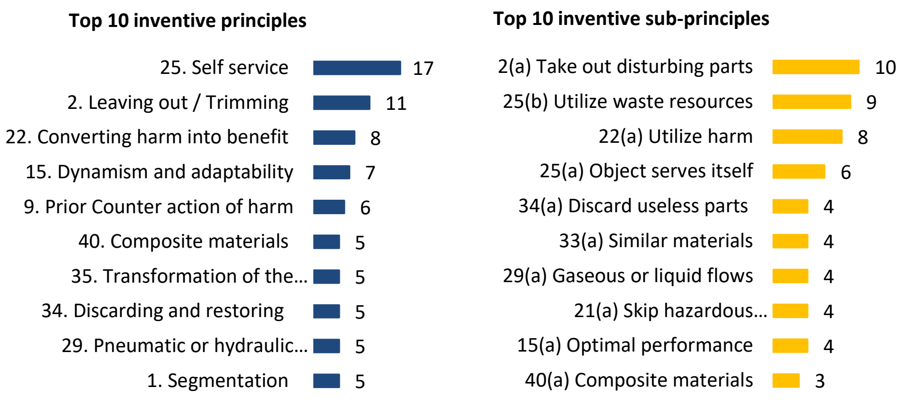

Fig. 4. Top 10 most frequently used TRIZ inventive principles and sub-principles extracted from 100 eco-patents (application frequency in 100 patents in %)

Reducing energy consumption and heat losses belong to one of the central environmental goals in process engineering. For that reason, the additional analysis of selected 38 eco-patents with this inventive task has been performed to identify typical solution principles applied to new technologies or equipment. The results outline two of the strongest principles especially for thermal and heat transfer processes: N25. Self-service (utilize waste or environmental resources) and N22. Converting harm into benefit. One application example of Principle 25. Self-service is given in US2017355617A1 which reduces energy consumption in thermal liquid desalination and distillation by repeatedly re-using thermal energy in the system. Another recent research study [25] examines the intensification of carbon capturing in the cement and iron/steel production using a temperature CO_2 adsorption process involving swirling or toroidal fluidized beds: the recovered waste heat in the cement and iron/steel processes can be used to cover high energy needs of the temperature swing adsorption.

2.6 Inventive Principles for Resolving Eco-Engineering Contradictions identified with the Contradiction Matrix

The classical 39x39 TRIZ Contradiction Matrix, also known as Altshuller Matrix [4], with 39 engineering parameters can be also used for identification of the inventive principles for eco-engineering contradictions with 5 ecologically relevant parameters, such as *Energy consumption of the moving object* (n.19), and *of the non-moving object* (n.20), *Energy losses* (n.22), *Material losses* (n.23), *Amount of substance* (n.26). All 39 parameters, including 5 eco-parameters and other 34 non-ecological parameters, together with instructions on how to apply the Altshuller Matrix are available on-line in [24].

In accordance with our analysis the 39x39 TRIZ matrix proposes solution principles for 281 primary and 15 secondary eco-contradictions regarding efficiency of energy or material utilization. The diagrams in Figure 5 present the top 10 TRIZ inventive principles recommended with the matrix for resolving

a) 65 primary eco-contradictions resulting from improvement of parameters *Energy consumption of the moving object* (n.19), *Energy consumption of the non-moving object* (n.20), and *Energy losses* (n.22) on the one hand, and worsening of the other 34 non-ecological parameters on the other hand.
b) 64 primary eco-contradictions resulting from improvement of parameters *Material losses* (n.23), *Amount of substance* (n.26) on the one hand, and worsening of the other 34 non-ecological parameters of the matrix on the other hand.

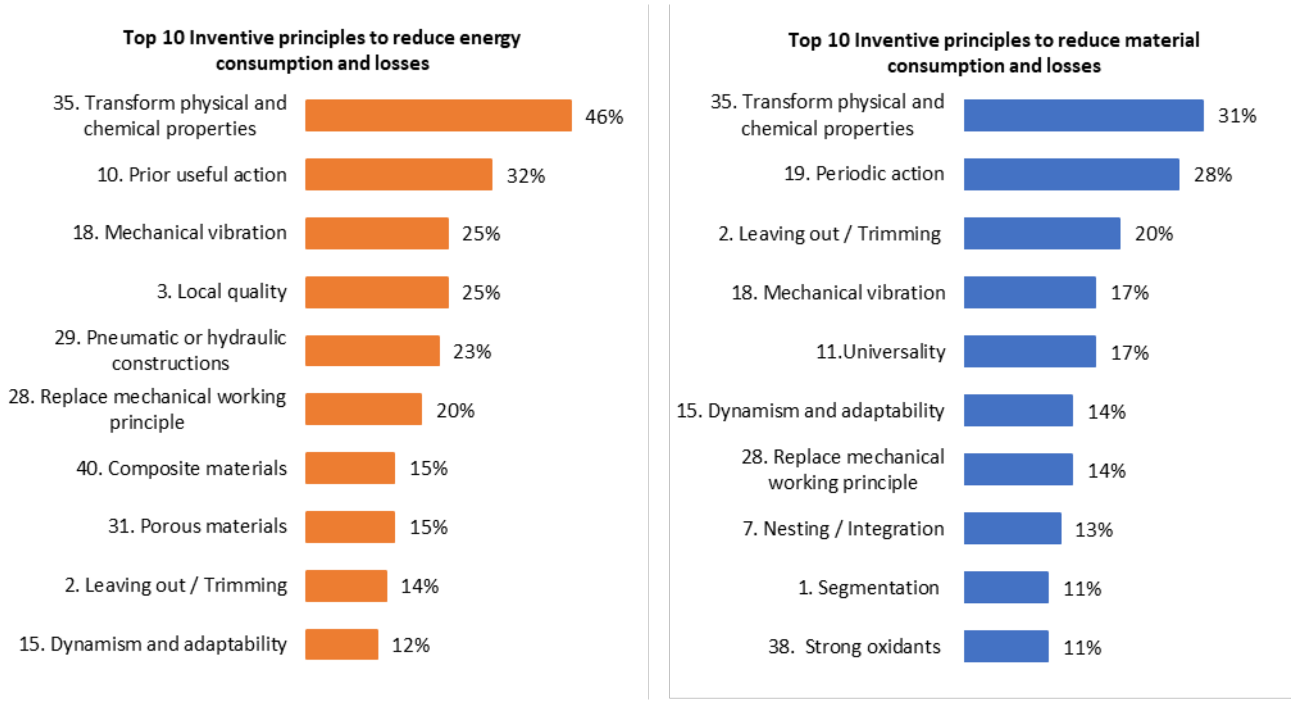

Fig. 5. Top 10 TRIZ inventive principles for primary eco-contradictions in order of their recommendation frequency by the 39x39 Contradiction Matrix

Comparing matrix recommendations in Fig. 5 with the inventive principles extracted from the list of eco-patents (Fig. 4) a low overlapping of these top 10 principles groups must be taken into account. Moreover, the application of the classical TRIZ matrix for other eco-innovation requirements is limited. An attempt to update the matrix and to increase the original list of 39 parameters to 50 was undertaken in 2003 and resulted in two additional eco-parameters such as *Noise* and *Harmful emissions* [26].

In general, a successful application of TRIZ inventive principles in eco-innovation requires higher qualification and creativity of engineers and needs methodical support.

Therefore, the existing approaches combining eco-design guidelines with TRIZ should enable engineers to identify and implement appropriate solutions faster in accordance with the objectives and constraints of their development tasks.

3 Eco-Innovation Methods using TRIZ

3.1 Brief Definitions of Eco-Design and Eco-Innovation

Eco-Design can be defined as an approach to improve or develop products or processes under consideration their environmental impacts during their entire lifecycle. The eco-innovation focuses on the integration of environmental aspects and requirements in the early stages of the innovation and new product development processes. In accordance to [27] eco-innovation includes "new or modified processes, practices, systems and products which benefit the environment and contribute to environmental sustainability". The International Organization for Standardization ISO issued numerous norms, guidelines, and tools. For example, the ISO14040:2006 describes the principles and framework for life cycle assessment (LCA), ISO14044:2006 provides LCA guidelines, and ISO14006:2011 provides guidelines to implement Eco-Design as part of an environmental management system (EMS) within companies.

A number of methods and tools have been developed to support the process of eco-innovation in the last two decades. To the best-known methods belong Eco-Compass [28], Life Cycle Design Strategy (LiDS Wheel) [29], Sustainability Circle [30], EcoDesign PILOT [31], Eco-Ideation Tool [16], Value Mapping Tool [32], Design for Environment (DfE) [33] and Quality Function Deployment for Environment (QFDE) [34, 35], EcoASIT [36], Eco-ideation stimulation meso-mechanisms ESMs [37], Green Engineering [38] with 12 Principles of Green Engineering [39], and other methods, presented in a comparative study of strategy- and ideation-oriented eco-innovation tools [40]. In the field of process engineering should be mentioned in first place Green Process Engineering [41] and Process Intensification (PI) [42], Process Design for Sustainability (PDfS) [21], and other approaches.

3.2 Process Intensification as a Knowledge-based Eco-Engineering Methodology

Process Intensification (PI) can be generally defined as a knowledge-based methodology leading to more efficient processes and equipment, characterised by reduced energy consumption and losses, raw material cost reduction, increased process flexibility, quality, safety, and better environmental performance [43, 42]. The concept of Process Intensification dates back to the research of Prof. Ramshaw and his colleagues [44, 45] and subsequently became more diverse in its implementation and practice, from the processes mainly involving gas/liquid systems to the solids handling [46]. Its modern application is not only limited to the chemical engineering and now includes environmental aspects of process engineering [42] and challenges of heat and mass transfer [25, 47].

The PI technological databases are continuously evolving and currently cover a wide range of more than 155 processing methods and equipment, such as equipment carrying out chemical reactions, operations not involving chemical reactions, multifunctional reactors, hybrid separation methods, alternative energy sources and others [42, 46]. As high energy consumption and energy losses were found as most frequently mentioned negative side effects in eco-engineering contradictions, the following 58 PI thermal operations and technologies, presented in Table 7, can be recommended for systematic solving of eco-problems.

Table 7. Example of 58 thermal operations, methods and equipment in Process Intensification

Thermal operation / equipment	**PI technologies**
Reactors (11)	Catalytic Plate Reactor (CPR), Heat Pipe Reactor, General HEX-Reactors, Alfa-Laval Plate Heat Exchanger Reactor, Heatric Diffusion Bonded Reactors, MarBond Reactor, Multiple Adiabatic-Bed PCR, Reverse Flow Reactor, ShimTec Compact HEX-Reactor, HiGee (Rotating Packed Bed), Static mixers
Distillation (10)	Reactive Distillation, Pervaporation-Assisted Reactive Distillation, Distillation - Dividing Wall Column, Cyclic Distillation, Fixed-Bed Adsorptive (FAD) Distillation, Suspension Adsorptive (SAD) Distillation, Extractive Distillation, Heat-Integrated Distillation, Membrane Distillation, Distillation – Pervaporation
Heat transfer equipment (8)	Nano-Fluids for Enhanced Heat Transfer, Additives (for Liquids/Gases) for Enhanced Heat Transfer, Treated Surface (Coatings) for Enhanced Heat Transfer, Extended Surfaces for Enhanced Heat Transfer, Acoustically Enhanced Boiling Heat Transfer, Surface Vibration for Enhanced Heat Transfer, Ultrasonic Fluid Vibration for Enhanced Heat Transfer, Electrostatic Fields for Enhanced Heat Transfer
Heat exchangers (7)	Plate Heat Exchanger, Printed Circuit Heat Exchanger (PCHE), Chart-flo Heat Exchanger, Polymer Film Heat Exchanger, Foam Heat Exchanger, Mesh Heat Exchanger, Micro Heat Exchanger
Crystallization (6)	Reactive Crystallization/Precipitation, Ultrasound-Enhanced Crystallization, Electric Field-Enhanced Crystallization, Electrostatic Precipitation (ESP), Extractive Crystallization, Membrane Crystallization
Heating (5)	Radio Frequency (RF) Heating, Microwave Heating, Induction Heating, Plasma Heating, Viscous Heating Devices
Extraction (4)	Reactive Extraction, Centrifugal Liquid-Liquid Contactors, Electric Field-Enhanced Extraction, Membrane Extraction
Drying (4)	Electric Drying and Dewatering, Membranes for Dehydration, Microwave Heating + Drying, Pulsed Combustion Drying
Condensation (1)	Reactive Condensation
Separation (1)	Cryogenic Separation
Gasification (1)	Plasma gasification

The top 10 TRIZ inventive principles and sub-principles, extracted from thermal PI technologies are presented in Fig. 6. They can be generally recommended for solving of eco-problems related to energy consumption and losses in process intensification.

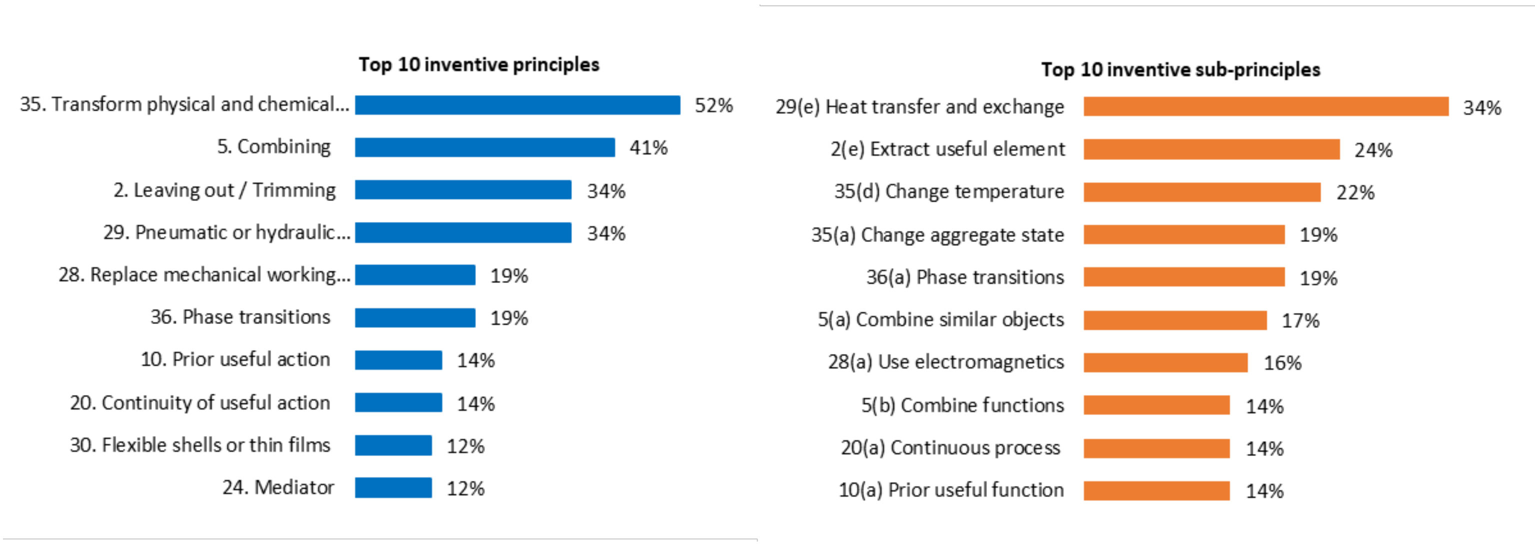

Fig. 6. Top 10 TRIZ inventive principles and sub-principles most frequently encountered in the 58 analyzed thermal operations and methods, presented in Table 7

It is also important to note here that some technological basics of PI [41, 46] are similar to the evolution laws and inventive principles of TRIZ [1]. For example, transition of operations from the macro- to meso- and micro-level as well as enhanced surface configurations known in PI, correspond to the TRIZ inventive principle *17. Shift to another dimension* (17b. Miniaturization; 17e. Two- and three-dimensional interactions). The PI principle of the force fields enhancement (mechanical - acoustic - electrical - electromagnetic - light energy) is equivalent to the TRIZ principle *28. Replace mechanical working principle.* Reasonably, that the PI researchers, then being unaware of TRIZ, could empirically propose conceptual techniques similar to TRIZ. For example, the majority of 15 process intensification strategies presented in [48] show parallels to some TRIZ inventive principles. Table 8 illustrates advantageous synergies of TRIZ and PI. In general, TRIZ inventive principles as more abstract and universal, whilst some of the intensification strategies in [48] can be seen as detailed illustrations or interpretations of TRIZ principles.

Table 8. Comparison of intensification strategies [48] with 40 TRIZ Inventive Principles.

15 PI strategies, adapted from [48]	40 TRIZ Inventive Principles [4, 23]
1. Modification of operating conditions: temperature, pressure, concentration 2. New solvents to reduce environmental impact of processes 3. Modification of fluid phase properties by change of pressure or temperature 6. Catalyst structuring and modification 8. Increasing shear rate 9. Change of material properties	35. Transformation of the physical and chemical properties: a) Change an object's aggregate state b) Change the object's concentration or consistency. c) Change other relevant physical properties or operational conditions (pressure, density, hardness, viscosity, conductivity, magnetism etc.), separately or together. d) Change the object's temperature. e) Change process chemistry, chemical properties or operational conditions: formulation, pH, solubility etc.
3. Modification of fluid phase properties by addition of gas bubbles or solid particles	40. Composite materials: composition of materials in different aggregate states (40e)
4. Inert species addition in multiphase flow: emulsifying additives, viscosifying agents	39. Inert environment. 24. Mediator: intermediate object (24a)
5. Geometric-structuring strategy and micro structuring,	17. Shift to another dimension: multi-dimensional interactions (17e), miniaturization (17b)
7. Gravity and use of centrifugal force	8. Anti-weight: use of gravitational or centrifugal force (8d)
10. Parallelism in the process, multi-scale design 15. Coupling with separation	5. Combining: parallel operations (5a), combine process steps to perform parallel or contiguous operations (5b)
11. Segmentation, non-uniform conditions.	1. Segmentation 3. Local quality: non-uniform structure or properties (3a)
12. Periodic operation	19. Periodic action
13. Phase contacting: choice of optimal residence time distribution to operate a reaction	15. Dynamism / Adaptability: enable optimal performance parameter at each stage of operation (20a)
14. Alternative energy sources	25. Self-service: use of waste (25b) and environmental (25c) resources

3.3 Evolution of Eco-Innovative Methods applying TRIZ

Since 2000 the Theory of Inventive Problem Solving TRIZ has been applied for development of cleaner and eco-friendly production processes with less material and energy losses, as presented in several reviews [49, 50, 51]. Table 9 summarises and chronologically sets out, with comments 66 selected eco-innovation methods using TRIZ elements or adaptions published between 2000 and 2018. Interestingly, the number of papers discussing TRIZ application for eco-innovation in the last 9 years (42 papers, in the years 2010-2018) has almost doubled in comparison with the previous decade with 24 papers in the years 2000-2009.

In general, TRIZ is considered as supporting ideation and creativity component of eco-innovation. A comparison of 28 of Eco-Design Methods and Tools given in [52] attests TRIZ the average level of complexity and time expenditures for its application but outlines no built-in life cycle perspective in TRIZ. At the same time a systematic literature review of existing practices on sustainability-oriented innovation (SOI) in Small and Medium Enterprises (SMEs) published in 2014 doesn't contain any references to TRIZ [53]. However, systematic eco-innovation support in SMEs with TRIZ is reported since 2011 [54, 55, 56]. The classical TRIZ contradiction matrix 39x39, which dates back to the extensive research of Altshuller and his co-workers in the 1970s [4], is the most frequently used and inspiring TRIZ tool in eco-ideation methods, followed by direct application of 40 inventive principles, evolution laws, effect databases. Numerous methods apply adapted or modified particular TRIZ elements or propose new tools based on the TRIZ basic concepts, such as ideality, multiscreen analysis etc. As an example of a successful TRIZ adaptation and consequent further development, one should mention the system of eco-innovation guidelines including more than 330 operators for problem definition and ideation [56, 57, 58].

At first sight, one can assume that the ideation potential of TRIZ has been tested and fully applied in eco-design. However, a closer observation of the TRIZ-based eco-innovation methods brings to light that on the whole the application of TRIZ still remains rather fragmented and undervalued within the research community and industry. For example, the analytical TRIZ tools for problem definition and identification of engineering contradictions such as Root-Conflict Analysis, Cause-Effect-Chain-Analysis, or Function Analysis [7, 9] seem to be not applied in eco-design. No significant progress has been reported regarding application of the function-oriented search (FOS) and data mining approaches in eco-innovation. The high efficiency of the Anticipatory Failure Identification [7, 59] for prevention of breakdowns and failures in new technologies and equipment is also underestimated. Even the inventive operators for solving eco-engineering contradictions are not systematically extracted or available for all application fields.

Table 9. Evolution of the eco-innovation methods applying TRIZ in 2000-2018.

	Reference	TRIZ integration or adaptation in eco-innovation method
1.	Jones and Harrison, 2000 [49]	Linking the headlines of 6 Eco-compass categories with 39 engineering parameters from classical TRIZ contradiction matrix.
2.	Low et al., 2000 [50], 2001 [60]	Assigns 9 parameters of 39x39 contradiction matrix to 4 general environmental parameters of eco-service design.
3.	Mann et al, 2001 [61]	Application of evolution trends, 40 inventive principles and Altshuller matrix 39x39.
4.	Chen and Liu, 2001 [62], [63]	Proposes a 39x7 matrix containing 39 TRIZ engineering parameters and 7 eco-efficiency elements; link to a green QFD [64].
5.	Chen, 2002 [12]	Ideality laws for green innovative design of products.
6.	Chen and Liu, 2003 [64]	Matrix containing 39 TRIZ engineering parameters and 7 eco-efficiency elements with a link to a green QFD [64].
7.	Wimmer et al., 2002 [31]	Application of classical TRIZ elements (Inventive principles, Physical effects) in ideation phase of the Eco-Design Pilot.

8.	Chang and Chen, 2003 [65]	Application of TRIZ classical contradiction matrix 39x39 in a step-by-step eco-design process.
9.	Chang and Chen, 2003 [66]	Eco-innovative product examples for 40 TRIZ inventive principles related to 7 eco-efficiency categories.
10.	Strasser and Wimmer, 2003 [67]	Combination of EcoDESIGN strategies and 40 TRIZ Inventive Principles. Contradiction analysis with Problem Formulator.
11.	Jones, 2003 [68]	Applies contradiction analysis, principles of Ideality, 40 inventive principles and evolution patterns for eco-ideation.
12.	Serban et al., 2004 [69]	Application of TRIZ inventive principles in Design for Environment. (DfE).
13.	Chang, 2004 [70]	A software-based eco-design method contains a 39x7 matrix with 39 TRIZ engineering parameters and 7 eco-efficiency elements.
14.	Chang and Chen, 2005 [71]	A step-by-step problem definition and solving method using TRIZ Substance-Field Analysis and its transformation rules.
15.	Yen and Chen, 2005 [72]	Combining the concept of green design with FMEA and 39x7 matrix with 39 engineering and 7 eco-efficiency parameters.
16.	Kobayashi, 2005 [73]	Supporting eco-innovative product design with 39x39 TRIZ contradiction matrix and 40 inventive principles.
17.	Justel et al., 2006 [74]	Environmentally friendly design for disassembly using 39x39 Altshuller matrix, 40 principles, separation principles.
18.	Fitzgerald et al., 2006 [75]	ENVRIZ methodology for Design for Environment adapting 39x39 Altshuller matrix and 40 inventive principles.
19.	Chen and Chen, 2007 [76]	Proposes 39x39 Altshuller contradiction matrix, 40 inventive principles, and substance-field analysis for eco-innovation in design for disassembly.
20.	Sakao, 2007 [77]	Design method (LCA and QFD for Environment) applies TRIZ 39x39 contradiction matrix, effects database and evolution laws.
21.	Dekoninck et al., 2007 [78]	Enhancing eco-ideation brainstorming with simplified TRIZ tools based on contradiction matrix and inventive principles.
22.	Regazzoni et al., 2009 [79]	Proposes 8 eco-guidelines with corresponding 19 rules based on 8 TRIZ evolution laws and Recourses Analysis.
23.	Fresner et al., 2010 [11]	Combining TRIZ laws of evolution with cleaner production strategies in eco-innovation.
24.	Sheng and Kok-Soo, 2010 [80]	Problem-solving guideline called TRIZEE applies 40 TRIZ inventive principle correlating with eco-efficiency elements.
25.	Fitzgerald et al., 2010 [15]	Identifies 62 eco-contradictions in 80 patents and 50 products with 21x6 innovation matrix with 6 eco-goals and 21 functional eco-parameters. 39x39 contradiction matrix, 40 inventive principles.
26.	D'Anna and Cascini, 2011 [81]	Proposes easy-to-use SUSTAINability Map tool, based on Evolution Laws of Engineering Systems and System Operator.
27.	Chulvi and Vidal, 2011 [82]	Analysis of relationship between 31 evolution trends known in TRIZ and eco-design strategies of LiDS Wheel.
28.	Russo et al., 2011 [83]	Offers eco-guidelines based on 8 TRIZ evolution laws and TRIZ concepts of Resources, Ideality and Ideal Final Result.
29.	Russo et al., 2011 [54]	330 eco-guidelines extracted from the TRIZ laws of evolution within the European project "Recycling and Resource Efficiency driving innovation in European Manufacturing SMEs.
30.	Trappey et al., 2011 [85]	Combing LCA, QFDE, back-propagation network BPN for new eco-innovation, supported by TRIZ inventive principles.

31. Yang and Chen, 2011 [86]	Combining Case-based Reasoning (CBR) and TRIZ: 39x7 matrix with 7 eco-efficiency elements, 40 inventive principles, 8 evolu-
32. Tsai et al., 2011 [87]	Eco-design framework adopting classical TRIZ tools: 40 inventive principles, inventive standards, evolution trends, ARIZ.
33. Yang and Chen, 2012 [88]	Combining TRIZ evolution laws with CBR, simple LCA and Expert systems.
34. Ferrer et al., 2012 [10]	Eco-design tool supports resolving technical or physical contradictions with TRIZ inventive principles and Su-Field Analysis
35. Russo and Birolini, 2012 [89]	Over 300 eco-guidelines in several subsets, adopted from TRIZ laws of evolution and inventive principles.
36. Negny et al., 2012 [90]	Method based on CBR and TRIZ applies physical, chemical, biological, geometrical effects and the resources-oriented search.
37. Durieux and Teulon, 2012 [91]	Eco-ideation using TRIZ contradiction matrix and inventive principles for improvement.
38. Hosseinpour and Peng, 2012 [92]	Sustainable design method using integration of Function Impact Matrix with Eco-checklist and TRIZ tools.
39. Mogensen and Rousse, 2012 [93]	Use of TRIZ tools for solving contradictions (inventive principles) on material, component and system levels.
40. Kallel et al., 2013 [94]	TRIZ contradiction matrix, Separation principles, Standard solutions used for problem solving and concept creation.
41. Tyl et al., 2013 [36]	Application of ASIT (simplified TRIZ) creativity principles adapted for ideation phase of eco-innovation processes.
42. Cherifi et al., 2014 [95]	Linking 5 eco-efficiency parameters to 39 engineering parameters of contradiction matrix; 40 inventive principles for ideation.
43. Russo et al., 2014 [58]	TRIZ-based eco-design matrix, “i-Tree” method for eco-design purposes and simplified for non-expert users.
44. Chen and Chen, 2014 [96]	Integration of Biomimetic Design and ARIZ.
45. Ben Moussa et al., 2014 [97]	Confirms applicability of TRIZ tools for the problem definition and solving in the field of green logistics
46. Russo and Serafini, 2015 [3]	Identification of eco-engineering contradictions with the proposed Contradiction Prompter method.
47. Russo et al., 2015 [56]	Framework of eco-guidelines with 330 TRIZ-based actions or operators for problem definition and ideation.
48. Pokhrel et al., 2015 [14]	Adapts TRIZ 39x39 contradiction matrix to a 14x14 matrix with 3 eco-engineering parameters and 8 solution principles.
49. Vidal et al., 2015 [98]	Linking TRIZ evolution trends and Eco-Design Strategy Wheel: proposal of 17 trends that potentially can impact eco-design.
50. Cluzel et al., 2016 [99]	Recommends the application of simplified TRIZ inventive principles (e.g. known in ASIT) to support LiDS Wheel.
51. Ko et al., 2016 [100]	Eco-contradiction matrix between customer needs and eco-efficiency elements; recommending TRIZ inventive principles.
52. Fayemi et al., 2016 [101]	Definition and combing of partial Idealities from different fields of expertise. TRIZ inventive and separation principles.
53. Ameknassi et al., 2016 [102]	Defines Eco-TRIZ for problem modeling and solving using 5 rules of Substance-Field-Analysis and 76 Standards solutions.
54. Ben Moussa et al., 2017 [103]	Analysis of applicability of the inventive algorithm ARIZ85 for solving Green Supply Chain problems.
55. Russo et al., 2017 [84]	Eco-innovative technique “IFR index”, for selecting the main LCA criticalities, adopted from TRIZ Concept of Ideal Final Result and using a set of eco-guidelines.

56.	Chen and Hung, 2017 [104]	Linking TRIZ inventive principles to biological cases for low-carbon eco-innovation strategy.
57.	Feniser et al., 2017 [55]	TRIZ integration in eco-innovation. Recommends laws of technical evolution, TRIZ inventive principles with eco-examples.
58.	Russo et al., 2017 [84]	Eco-innovative technique "IFR index", for selecting the main LCA criticalities, adopted from TRIZ Concept of Ideal Final Result and using a set of eco-guidelines,
59.	Bersano et al., 2017 [105]	Eco-design methodology based on abridged Life Cycle Assessment (aLCA) tools and more than 300 TRIZ-related eco guidelines
60.	Caligiana et al., 2017 [106]	Application of TRIZ and QFD for sustainable eco-friendly design process
61.	Maccioni et al., 2017 [57]	Analysis of ideation stimuli for sustainable design clustered in TRIZ ideality categories: useful functions, attenuation of undesired effects, reduction of consumed resources.
62.	Russo et al., 2017 [107]	Framework to build guidelines for eco-improvements, balancing the completeness and simplicity of eco-innovations tools, such as e.g. TRIZ based eco-guidelines.
63.	Chen, 2018 [108]	Kansei ECO TRIZ model using 39x39 Altshuller matrix and 40 inventive principles
64.	Livotov et al., 2018 [109]	Updated 40 TRIZ principles with 160 sub-principles for eco-problems in process engineering

4 TRIZ Inventive Principles for Resolving Eco-Contradictions

The analysis of 100 eco-patents (Fig. 4), 58 thermal operations and methods (Fig. 5), 144 eco-engineering contradictions in the Altshuller matrix (Fig. 6), and of the reviewed eco-innovation methods allows one to select the strongest TRIZ inventive principles for environmental problems in process engineering. The mean occurrence frequency of principles in 100 eco-patents and 58 thermal operations has been determined as a ranking metric and resulted in the following selection of top 15 principles presented in Table 10.

Additionally, the evaluated partial ranking of the sub-principles detects the statistically strongest inventive operators. The major benefit of applying strongest sub-principles can be characterized by the time-saving, more efficient and precise ideation. For example, the top 15 principles contain 61 sub-principles which should be applied by the engineers for problem solving. Among 61 sub-principles only 23 have a ranking higher than 0,01. Thus, the ideation activities can be focused on these strongest 23 sub-principles. The new enhanced version of 40 TRIZ principles with 160 sub-principles (2018), used in the analysis, is presented in the Appendix.

Table 10. Selection of TRIZ inventive principles for solving eco-contradictions.

Pos.	Inventive principle	Rank-ing	Corresponding sub-principles with their partial ranking
1	35 Transform physical and chemical properties	0,099	35a:0.033, 35b:0.028, 35d:0.034, 35e: 0.004.
2	02 Leaving out / Trimming	0,099	2a:0.053, 2b:0.003, 2c:0.007, 2e:0.036.
3	05 Combining	0,079	5a:0.030, 5b:0.034, 5c:0.01, 5d:0.005.
4	25 Self-service / Use of resources	0,076	25a:0.026, 25b:0.041, 25c:0.009.
5	29 Pneumatic or hydraulic constructions	0,073	29a:0,017, 29c:0.004, 29e: 0.052.
6	28 Replace mechanical working principle	0,041	28a:0.032, 28c:0.009.
7	15 Dynamism and adaptability	0,038	15a: 0.023, 15b:0.011, 15c:0.004.
8	22 Converting harm into benefit	0,034	22a: 0.034
9	10 Prior useful action	0,034	10a: 0.034
10	09 Prior Counteraction of harm	0,031	9a: 0.013, 9b:0.013, 9d:0.005.
11	01 Segmentation	0,029	1a:0.013, 1b:0.005, 1c:0.004, 1d:0.004, 1e:0.003.
12	34 Rejecting and regenerating parts	0,029	34a:0.025, 34b:0.004.
13	36 Phase transitions	0,028	36a:0.028
14	20 Continuity of useful action	0,025	20a:0.025
15	40 Composite materials	0,024	40a:0.015, 40c:0.009
(16)	24 Mediator	0,022	24a: 0.012, 24b: 0.010
(17)	03 Local quality	0,014	3a:0.011, 3b:0.003.
(18)	17 Shift to another dimension	0,010	17c: 0.005, 17e: 0.005
(19)	18 Mechanical vibration	0,009	18a:0.003, 18e: 0.006
(20)	19 Periodic action	0,003	19a: 0.003

Taking into consideration the evaluation of eco-contradictions in the Altshuller matrix and several literature sources five additional principles (Pos. 16-20 in Table 10) with lower ranking can be added to the list.

As shown in Table 11, TRIZ Inventive Principles can be grouped and displayed in the recommended order of application [110]. Generally, one starts with the 12 statistically strongest principles (Group 1), followed either by the principles for design problems (Group 2) or by the principles for specific problems in process engineering (Group 3). Characteristically, the identified 15 strongest inventive principles for eco-engineering problems, indicated in Table 11 in bold and italics, are distributed almost evenly over three groups. Moreover, six of them are identical with the statistically strongest inventive principles NN 35, 10, 1, 28, 2, 15.

Table 11. Groups of 40 TRIZ inventive principles with the highlighted strongest 15 inventive principles for eco-engineering problems (in bold and italics).

Group 1: 12 statistically strongest inventive principles	**Group 2:** 13 principles for solving design problems	**Group 3:** 15 principles for specific problems in process engineering
35. Transformation of physical and chemical properties ***10. Prior useful action*** ***1. Segmentation*** ***28. Replace mechanical working principle*** ***2. Leaving out / Trimming*** ***15. Dynamism and adaptability*** 19. Periodic action 3. Local quality 17. Shift to another dimension 13. Inversion 18. Mechanical vibration 26. Copying and Modeling	6. Universality ***5. Combining*** ***29. Pneumatic or hydraulic constructions*** 30. Flexible shells or thin films 7. Nesting / Integration 8. Anti-weight 4. Asymmetry ***40. Composite materials*** 24. Mediator 14. Sphericity and Rotation 23. Feedback and automation 31. Porous materials ***25. Self-service / Use of resources***	16. Partial or excessive action 27. Disposability / Cheap short living objects ***20. Continuity of useful action*** 32. Change colour 21. Skipping / Rushing through 11. Preventive measure / Cushion in advance 33. Homogeneity ***22. Converting harm into benefit*** 39. Inert environment 37. Thermal expansion ***36. Phase transitions*** 38. Strong oxidants ***34. Rejecting and regenerating parts*** 12. Equipotentiality ***9. Prior counteraction of harm***

5 Concluding Remarks and Outlook

The objective of the presented research was to reveal primary and secondary eco-problems in process engineering and especially in the field of intensification of processes involving solids handling. The performed full-text analysis of 100 patent documents dealing with eco-problems resulted in the identification of large amount of secondary eco-contradictions, characterized by the situation at which solving of the primary eco-problem causes an additional ecological negative effect. It was shown that high energy consumption or losses, air pollution and acidification belong to the major negative side effects in eco-contradictions.

Secondary eco-contradictions can be documented and predicted with the help of correlation matrices of dynamically variable format, starting with 14x14 environmental categories as input parameters. The future analysis should clarify how adjustment of matrix resolution can improve the accuracy of contradiction identification. Also, the patent analysis can be partially or completely automated by means of data mining and processing, in order to reduce the currently high time expenditures for identification of invention goals, secondary problems and their correlations.

Additionally, a set of top 15 TRIZ inventive principles most frequently used in inventions dealing with eco-problems was extracted from the patent literature and PI technologies. It can be generally suggested for the practical use not only in process engineering. A future analysis should validate and refine given recommendations.

Since the implementation of eco-friendly solutions often causes secondary problems, TRIZ methodology can limit these negative side effects. The review of more than 60 eco-design approaches and methods using TRIZ confirms this statement. The TRIZ principles of Ideality, Resource-oriented and compromise-free problem solving fit in perfectly with the strategy of sustainable eco-innovation. On the one hand, the application of the TRIZ-based approaches helps to identify secondary problems, to predict and creatively solve eco-contradictions in advance. And 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. The authors advocate the approach of a comprehensive adaptable TRIZ-based toolbox and intuitively-to-use best-practice recommendations for its seamless integration into existing Eco-Design and Eco-Innovation framework, not only in the field of process engineering.

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Appendix. TRIZ Inventive Principles with 160 sup-principles for Process Engineering adapted from [23] without description and examples.

1. **Segmentation**: 1(a) Segment object; 1(b) Dismountable design; 1(c) Segment to microlevel; 1(d) Segment function; 1(e) Segment process.
2. **Leaving out / Trimming**: 2(a) Take out disturbing parts; 2(b) Trim components; 2(c) Trim functions; 2(d) Trim process steps; 2(e) Extract useful element.
3. **Local quality**: 3(a) Non-uniform object; 3(b) Non-uniform environment; 3(c) Different functions; 3(d) Optimal conditions; 3(e) Opposite properties.
4. **Asymmetry**: 4(a) Asymmetry; 4(b) Enhance asymmetry; 4(c) Back to symmetry.
5. **Combining**; 5(a) Combine similar objects; 5(b) Combine functions; 5(c) Combine different properties; 5(d) Combine complementary properties; 5(e) Combine opposing properties.
6. **Universality**: 6(a) Universal object; 6(b) Universal process.
7. **Nesting / Integration**: 7(a) Nested objects; 7(b) Passing through cavities; 7(c) Telescopic systems.

8. **Anti-weight**: 8(a) Use counterweight; 8(b) Buoyancy; 8(c) Aero- or hydrodynamics; 8(d) Use gravitational or centrifugal forces.
9. **Prior Counteraction of harm**: 9(a) Counter harm in advance; 9(b) Anti-stress; 9(c) Cooling in advance; 9(d) Rigid construction.
10. **Prior useful action**: 10(a) Prior useful function; 10(b) Pre-arrange objects; 10(c) Prior process step.
11. **Preventive measure / Cushion in advance**: 11(a) Safety cushion; 11(b) Preventive measures.
12. **Equipotentiality**: 12(a) Keep altitude; 12(b) Equipotentiality; 12(c) Avoid fluctuations.
13. **Inversion**: 13(a) Inversed action; 13(b) Make fixed parts to movable; 13(c) Upside down; 13(d) Reversed sequence; 13(e) Invert environment.
14. **Sphericity and Rotation**: 14(a) Ball-shaped forms; 14(b) Spheres and cylinders; 14(c) Rotary motion; 14(d) Swirling motion; 14(e) Centrifugal forces.
15. **Dynamism and adaptability**: 15(a) Optimal performance; 15(b) Adaptive object; 15(c) Adaptive process; 15(d) Flexible elements; 15(e) Change statics to dynamics
16. **Partial or excessive action**: 16(a) One step back from ideal; 16(b) Optimal substance amount; 16(c) Optimal action.
17. **Shift to another dimension**: 17(a) Multi-dimensional form; 17(b) Miniaturization; 17(c) Multi-layered structure; 17(d) Tilt object; 17(e) 3D interaction.
18. **Mechanical vibration**: 18(a) Oscillate object; 18(b) Ultrasound; 18(c) Resonance; 18(d) Piezo-electric vibrators; 18(e) Ultrasound with other fields.
19. **Periodic action**: 19(a) Periodic action; 19(b) Change frequency; 19(c) Use pauses; 19(d) Match frequencies; 19(e) Separate in time.
20. **Continuity of useful action**: 20(a) Continuous process; 20(b) Operate at full load; 20(c) Eliminate idle work.
21. **Skipping / Rushing through**: 21(a) Skip hazardous operations; 21(b) Boost the process.
22. **Converting harm into benefit**: 22(a) Utilize harm; 22(b) Remove harm with harm; 22(c) Amplify harm to avoid it.
23. **Feedback and automation**: 23(a) Introduce feedback; 23(b) Enhance feedback; 23(c) Automation; 23(d) Data processing.
24. **Mediator**: 24(a) Intermediate object; 24(b) Temporary mediator; 24(c) Intermediary process.
25. **Self-service / Use of resources**: 25(a) Object serves itself; 25(b) Utilize waste resources; 25(c) Use environmental resources.
26. **Copying: 26(a) Simple copies**; 26(b) Optical copies; 26(c) Invisible copies; 26(d) Digital models; 26(e) Virtual reality.
27. **Disposability / cheap short-living objects**: 27(a) Short-living objects; 27(b) Multiple cheap objects; 27(c) One-way objects; 27(d) Create objects from resources.
28. **Replace mechanical working principle**: 28(a) Use electromagnetics; 28(b) Optical systems; 28(c) Acoustic system; 28(d) Chemical and biosystems; 28(e) Magnetic particles and fluids.

29. **Pneumatic or hydraulic constructions**: 29(a) Gaseous or liquid flows; 29(b) Gas or liquid under pressure; 29(c) Use vacuum; 29(d) Fluidization; 29(e) Heat transfer and exchange.
30. **Flexible shells or thin films**: 30(a) Flexible shells or films; 30(b) Flexible isolation; 30(c) Piezoelectric foils; 30(d) Use rushes; 30(e) Use membranes.
31. **Porous material**: 31(a) Add porous elements; 31(b) Fill pores with substance; 31(c) Use capillary effects; 31(d) Physical effects and porosity; 31(e) Structured porosity.
32. **Change colour**: 32(a) Change colour; 32(b) Change transparency; 32(c) Coloured additives; 32(d) Use tracer.
33. **Homogeneity**: 33(a) Similar materials; 33(b) Similar properties; 33(c) Uniform properties.
34. **Rejecting and regenerating parts**: 34(a) Discard useless parts; 34(b) Restore parts; 34 (c) Create parts on time and on site.
35. **Transform physical and chemical properties**: 35(a) Change aggregate state; 35(b) Change concentration; 35(c) Change physical properties; 35(d) Change temperature; 35(e) Change chemical properties.
36. **Phase transitions**: 36(a) Phase transitions; 36(b) 2nd order phase transitions
37. Thermal expansion: 37(a) Thermal expansion; 37(b) Bi-metals; 37(c) Heat shrinking; 37(d) Shape memory.
38. **Strong Oxidants**: 38(a) Oxygen-enriched air; 38(b) Use pure oxygen; 38(c) Use ionized oxygen; 38(d) Use ozone; 38(e) Strong oxidants.
39. **Inert environment**: 39(a) Inert environment; 39(b) Inert atmosphere process; 39(c) Process in vacuum; 39(d) Inert coatings or additives; 39(e) Use foams.
40. **Composite materials**: 40(a) Composite materials; 40(b) Use anisotropic properties; 40(c) Additives in composites; 40(d) Composite microstructure; 40(e) Combine different aggregate states.

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