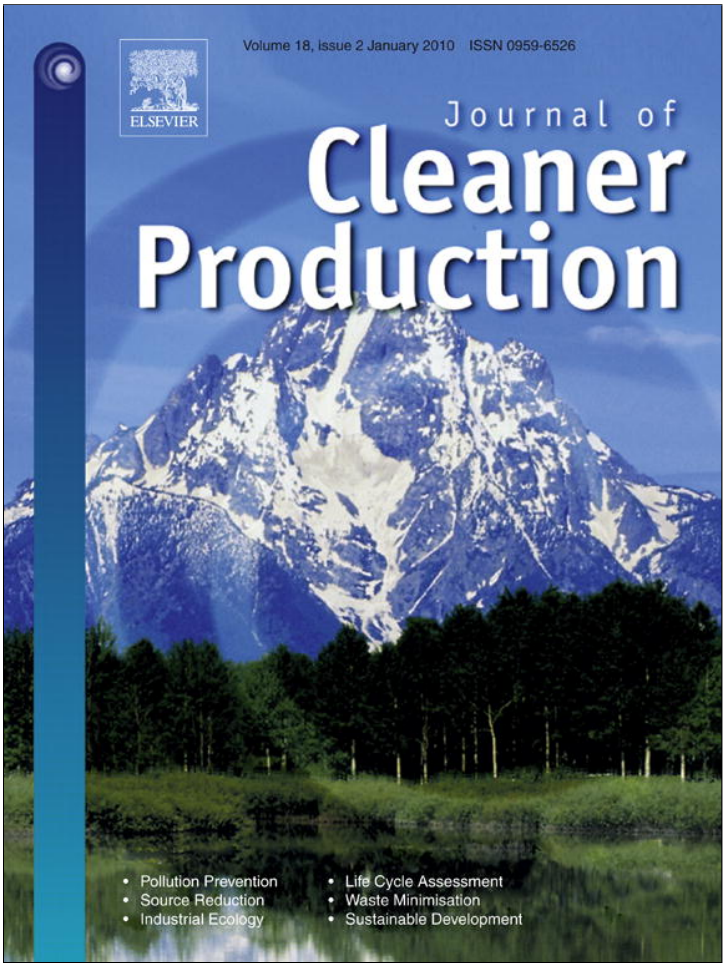
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The theory of inventive problem solving (TRIZ) as option generation tool within cleaner production projects

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ABSTRACT

Cleaner Production is an organized approach to minimize industrial waste and emissions by increasing the efficiency of the use of materials and energy. It is propagated especially by UNIDO and UNEP as an approach to identify preventive measures to cut on waste and emissions from industrial activities. Case studies conducted by the authors in the last 10 years demonstrate, that in a number of cases water consumption per production unit of industries from the surface treatment sector, from food processing and from the textile industry could be reduced by 30–90%, auxiliary materials consumption could be reduced by 30–50%, and energy consumption of processes could be reduced by 15–25%. All these measures were actually economically beneficial for the companies, most of these measures paid back in less than one year [1].

The standard approach to apply Cleaner Production originates from chemical engineering. It follows the steps of: Drawing a process flow sheet – collecting input/output data – doing mass and energy balances – identify sources for waste and emissions – set priorities – identify options. In the process of option generation one generally relies on expert knowledge or on checklists which are available in different manuals or in the best available technology reference (BREF) notes.[1] This approach is strong with teams with an (chemical) engineering background.

The authors wanted to develop a generic approach for option identification especially for teams with little formal engineering background or teams which have to go beyond their professional experience by using elements of the so-called TRIZ method (Theory of inventive problem solving, or originally Russian: "теория решения изобретательских задач" (Teoria reschenija isobretatjelskich sadatsch)). TRIZ offers very strong tools for developing process improvement options on a generic level without specific technological knowledge about the process which shall be improved. The authors have found from their research that especially the concept of the Ideal Final Result, and the Laws of Evolution form a conceptual framework which can aid effectively in the identification of improvement options in a systematic way.

1. Cleaner production in a nutshell

Production-integrated – or preventive – environmental protection aims at reducing the amount and danger of waste and emissions and – as a consequence – also the costs for raw materials, water, and energy. Compared to the disposal of waste and to end-of-pipe technologies preventive environmental action offers several advantages:

- Reducing waste and emission generally means using smaller quantities of materials and energy, which has the potential for economic savings
- Reduction of waste and emissions usually triggers an innovative process in the company because of the intensive focus on the analysis production processes
- Risks regarding environmental liability and disposal are reduced to a minimum
- Reduction of waste and emissions means moving towards sustainable economic development

In traditional waste management the question is:

- What is to be done with the waste and emissions generated?

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[1] The BREF-notes are documents developed by the European Commission to support companies and the relevant authorities in the process of upgrading their technology to best practice standards, as required by the IPPC directive (Integrated Pollution Prevention and Control; Directive 2008/1/EC). They state best practise regarding pollution prevention for most industrial sectors.

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Preventive, integrated environmental protection on the other hand asks:

- Where do waste and emissions in my company come from?
- Why have they become waste and what can we do to minimize their generation?

Main tools of cleaner production are flow sheeting, and material and energy balances [1,2]. Flow sheeting uses black box modelling of process steps as a tool. This provides for a quick overview, especially of complex manufacturing processes. However, it does not necessarily analyse the activities within these black boxes in detail. It therefore depends also on the skills and experience of the expert building the black box model to do it detailed enough to account for process steps relevant in identification of sources of waste and emissions but keep it simple enough to keep the model manageable. Data for material and energy balances often can be taken from accounts (for a year), but have to be weighed and measured for more detailed balances. This makes this step time consuming and sometimes difficult in practise, if process documentation is not in place and has to be developed for the CP project.

Out of experience, a systematic representation of cleaner production strategies has been developed.

Generally, cleaner production strategies aim at the optimisation of material and energy flows by process modification (change of raw materials, changes in operational practise, technological changes), internal and external recycling. The following table gives an overview of interpretations of these strategies (Tables 1 and 2).

These strategies act as general principles. In a cleaner production project, firstly waste and emissions will be identified, quantified, prioritized according to the monetary value of waste materials calculated from the price of raw materials, energy, and processing, and energy and because of hazards involved in manipulating materials. Consequently in a team session involving plant personnel and external consultants during a brainstorming these principles are used to generate ideas which then can be used to minimise waste and emissions. This works nicely, if at least somebody in the team knows from experience or training about options which can be applied to the case.

Table 1
Cleaner production strategies.

CP Strategy	Description
Changes in operational practises	Standardization of processes (training) Control (improve accounting, create responsibilities, Improvement of process utilisation Improvement of dosage (see standardisation) Longer intervals for changes of auxiliary materials Improvement of procurement (see raw materials)
Change of raw materials	Use of less toxic materials (organic solvents, halogenated solvents, petrochemical products, cleaner raw materials, less asbestos, less heavy metals) Use of waste materials Use of less different materials
Technological change	Use mechanical processes instead of physical or chemical ones Use of counter flow processes Separation of waste Improvement of process conditions Improvement of energy efficiency of processes (by insulation, heat recovery) Reduction of drag in of impurities
Internal recycling	Re-use of material Re-use of structure Re-use of energy
External recycling	Re-use of material Re-use of structure Re-use of energy, e.g. for district heating

Table 2
Specific examples for cleaner production strategies for metal manufacturing and the textile industries.

CP Strategy	Example
Changes in operational practises	- documentation of key process data (consumption of water, energy, chemicals) - use of indicators for process analysis and control - switching off equipment which is not used - planning production so that it is as continuous as possible (to minimize start up, shut down, idle phases)
Change of raw materials	- use of water based paints instead of solvent based paints - use of water based degreaser instead of solvents - replacement of asbestos fibre insulation materials by mineral wool - replacement of cyanides in galvanising - use of heavy metal free dyes in the dyeing of textiles
Change of technology	- installing a humidity sensor and automatic control of airflow in a tenter - installing a three-stage counter flow rinsing cascade in a galvanising plant - improvement of process conditions by automatic dosing pumps for the process chemicals - removal of water by pressing and by vacuum from fabrics before thermal drying
Internal recycling	- shreddering gate system in injection moulding and mixing the granulate to the raw material - reusing heated cooling water in cleaning the plant
External recycling	- use of returnable packing system - use of process waste heat to heat office buildings - recycling of polyethylene film through re-granulation

Most of the environmental managers working on Cleaner Production projects, however, seem to have little formal higher technical education. A recent survey of 45 companies currently participating in the Ecoprofit Club in the City of Graz done by the authors shows, that 24% are skilled workers, 22% have a high school degree, 22% a technical high school degree, 10% an University degree in natural science (master), 9% a business degree, 6% a law degree, and 7% an engineering degree. None had a chemical engineering degree.

Therefore the authors were looking for an approach:

- Which is applicable without chemical engineering training
- Which includes tools which use a modelling language as close to natural language as possible
- Which is helping groups to go beyond the knowledge they have from their own training and experience in the identification of options for improvement

2. Cleaner production and TRIZ – a comparison

TRIZ was defined by Russian researchers from the 1940s on as the "Theory of inventive problem solving". These researchers, pioneered by Genrich Altshuller looked for fundamental principles of inventive problem solving. Altshuller analysed a big number of Russian patents for generic principles how the patented solutions were arrived at. He identified the following laws of evolution of technical systems:

1. Stepwise evolution of systems: systems evolve in discrete steps.
2. Increasing ideality[2]: systems evolve towards ideality, characterized by supplying the technical function without causing any harmful effects (in terms of effort, resource consumption, etc.)

[2] "Ideality" in TRIZ is defined as: total of useful functions over total of harmful functions (harmful functions include waste and cost), functions are defined strictly from a client's perspective.

3. Different evolution of system elements: system elements evolve on different levels
4. Increase in dynamics and control: systems are dynamized, control increases over evolution
5. Increase in complexity and decrease again: the complexity of a system increases and decreases again after reaching a certain level of complexity
6. Increase of coordination: the rhythm of the different elements of a technical system becomes more and more coordinated
7. Miniaturisation: the system and its elements tend to become miniaturized
8. Decrease in human interaction: Human interaction with the system decreases with evolution

The authors found during their analysis, that the eight TRIZ principles show similarities and some correspondence to the strategies of Cleaner Production. Table 3 compares the strategies of Cleaner Production to the Laws of Evolution as defined by Genrich Altshuller [3].

Genrich Altshuller also found, that the process of inventing actually means to locate "contradictions" in a system, which keeps it from performing according to the ideal solution, and to solve them. Contradictions can be either technical, or physical. Technical contradictions appear, when there are conflicting requirements regarding two different parameters of a technical system (e.g. the display of a laptop should be bright, and the life of the battery should be long, at the same time). Physical contradictions appear, when the same parameter should show different properties at the same time (e.g. a coffee mug should be hot (to keep the coffee hot) and cold at the same time (to allow to touch it). If the underlying physical contradiction can be identified, it usually can be solved by:

- Separating the system in time (change properties, so that they can vary in time and thus comply: store the coffee first in an insulated mug and transfer it to a cup just before serving it)
- Separating the system in space (change properties, so that they can vary locally and thus comply: e.g. adding a handle to the coffee mug)
- Separating the boundary conditions (e.g. change the process of coffee making to instant coffee which can be prepared at a lower temperature)

A full explanation of these separation principles can be found in Ref. [4]. The process of problem analysis, identification of technical contradictions, transferring them to physical ones and solving them later on was codified and called ARIZ [5].

Scholars of Altshuller later on worked on rephrasing the laws of evolution to facilitate their application. An easy to apply version are the so-called "Lines of evolution" [4].

TRIZ was applied in a number of companies in the last 20 years to solve different problems (among them Procter & Gamble, Ford Motor Company, Boeing, Philips Semiconductors, Samsung, LG Electronics). TRIZ applications to the design of products in cooperating sustainability and eco-efficiency related problems are documented in the literature, however rare [6–10]. Explicit use of TRIZ within CP is not documented until today, according to the knowledge of the authors. TRIZ, however, has been used within six sigma projects effectively [11].

This comparison of CP and TRIZ indicates, that – using the language of TRIZ – CP actually focuses on understanding optimum process conditions, optimising control and reducing human interaction to develop the process towards the ideal result and the ideal process. The ideal result in CP is defined by reaching the main useful function of the process in the absence of waste and emissions, minimum generation of by products, and minimum consumption of water and energy and thus minimum unnecessary cost. This formulation of Cleaner Production using the definitions of TRIZ can lead to a more generic definition of the concept of Cleaner Production as compared to the strategies of Cleaner Production.

The appropriate optimisation strategy can be derived from the concept of the ideal final result (Fig. 1). The TRIZ algorithm requires that at the beginning of the problem solving process a model of the current situation should be developed, picturing it accurately, showing the elements of the problem and their interactions, together with the resources available for problem solving. This is called function analysis. A function analysis models a technical system as a system of components and functions. A function is an activity, by which one component of a system changes a property of another component (Subject changes a property of an object). The definition of functions is similar to describing activities in natural language, and therefore easy to comprehend and apply also for non-technical members of the team. The function model literally opens up the black box models of process steps normally used in CP. It very quickly guides to the elements of a problem that require change and very often also helps to trigger suggestions how to change.

On the basis of the function model, the ideal final result is developed. The ideal final result is defined as the delivery of the main useful function of the system without any harmful functions. This analogy then is taken as a starting point for the identification of a practical realization.

If the model of the ideal final result cannot be translated into a practical solution, a backcasting procedure is recommended. Starting with the question: what keeps us from realizing the ideal solution, intermediate stages for problem solving are identified and again corresponding potential solutions. When again no corresponding practical solution can be identified, this step is repeated, until solutions have been found [12].

Grawatsch uses the following questions in the optimisation procedure after defining the ideal final result (as defined by achieving the desired function of the process without cost or harm) [13]. Grawatsch calls this process "trimming":

- Can components or (ancillary) functions be gotten rid of?
- Can the need for a function be eliminated?
- Can functions of other components or the components themselves be taken over?
- Can unwanted functions be eliminated by other functions?
- Can operating components be replaced by other components?
- Can operating components be replaced by existing resources?
- Can the system take over functions itself?
- Can freely available resources be used?

These questions are derived from the Laws of Evolution and can be correlated to these (Table 4). These questions can be considered as a very basic representation of TRIZ problem solving knowledge.

For example, the application of the trimming procedure to rinsing in galvanising would produce the following reasoning:

The problem is the consumption of rinsing water used to dilute the film of dragged out chemicals on the surface of the parts.

A brief excursion: During the analysis the question could be raised, whether the parts require galvanic surface treatment or whether the process could be avoided at all by applying alternatives, like powder coating. This is a justified question, which needs to be analysed. To ask this question in many applications will be out of the scope for small and medium sized enterprises which use processes specified by their suppliers. In some cases truly new process alternatives can be initiated by asking this fundamental question.

Table 3
Comparison of the strategies of cleaner production and the laws of evolution.

CP strategy → Line of evolution ↓	New raw materials	Changes in operational practises	Internal recycling	External recycling	Technology change	Product redesign
Stepwise evolution of systems	Acquiring Material safety data sheets, evaluating them, using them in supply chain management	Improved organisation of processes, continuous control, full implementation of management system	Separate useful fractions, reuse them, install continuous process	Separate useful fractions, find application, install continuous process	Mechanical instead of physical or chemical (decrease number of transformations)	New materials, new technologies, new manufacturing processes
Increasing ideality	Purer raw materials, with less toxic substances	Narrow process conditions to optimum conditions	Close cycles internally (e.g. cooling water, vapour recompression)	Industrial Ecology	Reduce drag in, improve process conditions, improve mixing, avoid dead zones	Avoid harmful materials, longer life
Different evolution of system elements	New materials with special properties to replace standard ones	Less developed components are typically control of utilities and auxiliary materials	Technology used in sensors, controls, drives	Quality control of waste	Heaters, drives, controls	New materials, new manufacturing processes
Increase in dynamics and control	Automatic control of dosage	Organisation, control, standardisation	Conditional internal recycling (e.g. by conductivity control)	Considering feedback from external companies regarding specifications	Counter current flow, cascaded use, Energy efficient systems	Use of recycled materials
Increase in complexity and decrease again	Automatic dye preparation system, finally based on three elementary colours only	Integrated management systems	Process integrated internal recycling (runners in injection moulding), reactants in chemical processes	Waste separation, replaced by application for mixed waste (yarns for carpets, plastic for fuel)	Separate waste	Integration of additional functions
Increase in coordination	Electronic purchasing, automatic stock control	Improving utilisation of plants, synchronise processes, preparatory action	Reuse waste in same process immediately	Customer specifications for accepting by products	Size/speed of equipment, preliminary action	Design for recycling
Miniaturisation	High tensile steel, thinner film	5S: minimize stock	Minimize hold-up, high pressure cleaning instead of flushing	Continuous supply	Micro reactors, use of staged systems	Integration of electronic elements, sensors
Decrease in human interaction	Preformulation of tailored formulations	Automatic process control	Automatic recycling (coolant, water)	Automatic sorting (e.g. glass, paper)	Automatic control	Automatic functions (calibration)

Assuming we need galvanic treatment, the ideal final result for rinsing in galvanising would be a surface free from contaminants ready for the next process step, without any harmful functions (wastewater, waste, and energy consumption). In process optimisation we can get closer to this goal by the elimination of the adhering film on the work piece from the very beginning, as this is causing the need for rinsing and the need for rinsing defines the use of water, the rinsing technology, etc.

In order to identify the useful function and the harmful functions of a process, a function analysis of the relevant process steps generating waste and emissions is performed. A plant consisting of a pickling tank and a rinsing water tank has the following elements:

- Parts
- Oxide
- Racks
- Acid solution

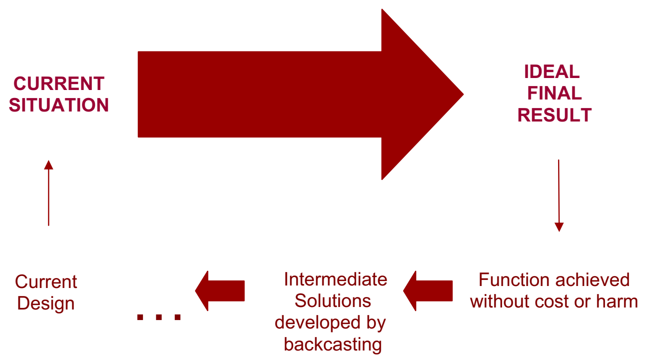

Fig. 1. Solving optimisation problems using the Ideal Final Result [13] and backcasting.

Table 4
Comparing the questions of the trimming procedure to the laws of evolution.

Laws of Evolution	Corresponding optimisation questions
Stepwise evolution of systems	Can the need for a function be eliminated?
Increasing ideality	Can operating components be replaced by existing resources (free, perfect, now)?
Different evolution of system elements	Can operating components be replaced by other ones (more advanced ones)?
Increase in dynamics and control	Can the system take over functions itself?
Increase in complexity and decrease again	Can components or functions be gotten rid of?
Increase of coordination	Can unwanted functions be eliminated by other functions?
Miniaturisation	Can operating components be replaced by other ones (smaller ones)?
Decrease in human interaction	Can unwanted functions be eliminated by other functions (automatic control)?

- Acid tank
- Rinsing water tank
- Rinsing water
- Valve
- Operator
- Crane, etc.

The plant is modelled in a function analysis in the following way (Fig. 2):

- Acid bath dissolves oxide (main useful function)
- Acid bath adheres to surface (of part)
- Parts hold an acid bath film
- Rinsing water dilutes acid film
- Valve controls water (flow)
- Operator opens valve
- Racks hold parts
- Crane holds racks
- Operator measures concentration (of acid in tanks)
- Operator adds acid
- Water generates wastewater
- Oxide reduces activity of bath
- Acid bath generates spent bath, etc.

Except from the one useful function, all other functions are actually harmful: they do not contribute to the goal of the process, and cause cost or waste or emissions.

Applying the questions from above after a function analysis and the definition of the ideal final result gives the following results (Table 5):

Possible solutions according to the definition of the Ideal final result asking Grawatsch's questions would be:

- No adhering film to work piece (e.g. by using surfactants which facilitate perfect draining because of low surface tension)
- Maximum reduction of drag out (e.g. by longer dripping times to allow perfect draining)

If these solutions cannot be realised, the solution finding process would propagate back from the ideal final result asking the question: What is the next best solution?

In the case of the rinsing problem this solution could be:

- Most effective dilution of adhering film to the concentration tolerable in the next process step
- Optimum reuse of rinsing water if we cannot avoid rinsing (e.g. by cascading rinsing water)
- Optimum use of water (e.g. by defining a rinsing criterion and measuring the conductivity of the effluent water)

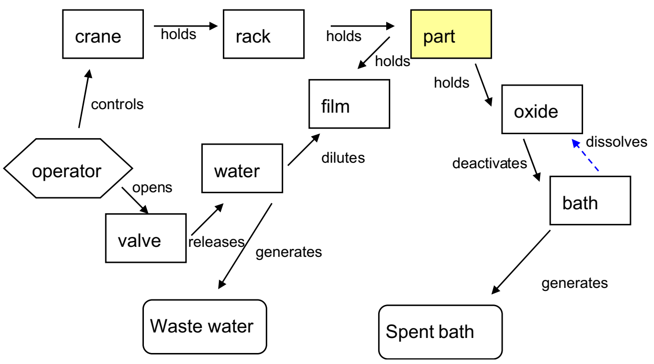

Fig. 2. Function analysis of the pickling process (dotted line: useful function, full lines: harmful functions, boxes: elements of the system, rounded boxes waste, hexagon: super system).

Table 5
Backcasting as problem solving approach in optimising a galvanising plant (ideal final result: minimum adhering film of active bath, minimum necessary dilution of this film).

Question for backcasting from ideal final result	Questions risen during function modelling	Examples
Can the need for a function be eliminated?	How can the need for rinsing with water be eliminated?	Reducing drag out by longer dripping times, mounting parts at angles, avoid scooping, defining proper rinsing criteria,
Can components be gotten rid of?	Which components of the galvanising system (surface of parts, racks, drag out) can be gotten rid of?	Reduce drag in of impurities (grease, oil), Reduce surface area of parts, but also of racks Reduce components which increase viscosity of solutions (by reducing the contents of metals)
Can functions be taken over by other components?	Can components be introduced which can perform the functions of diluting the adhering film?	Cascade, spray rinses
Can unwanted functions be taken over by other functions?	Can dilution of adhering film be achieved in a different way?	Blowing, use of recycled water, reduce viscosity of films by increasing temperature
Can the system take over functions itself?	Which functions of the galvanising system can be assigned to the system itself?	Conductivity control of rinsing water, automatic control of the crane to guarantee dipping and draining times
Can operating components be replaced by existing resources?	Which components could be replaced by plant resources (heat, pressurized air)?	Air blowing to blow of drag out
Can free resources be used (time, air, space …)?	Can resources like air, time, and space help to improve the system?	Improve dripping time, overflow in rinsing cascades by gravity

3. Case study: ZERMEG (Zero emission retrofitting for five existing galvanising plants)

The approach described above was used in later stages of the project "ZERMEG". The ZERMEG project was carried out within the framework of the Fabrik der Zukunft ('Factory of the Future') programme, and was commissioned by the FFG, the Austrian Research Funds, and BMVIT, the Austrian ministry for innovation and transport [14].

ZERMEG stands for 'Zero emission retrofitting method for existing galvanising plants'. ZERMEG's aim is to define a method to achieve the implementation of measures to modernise existing galvanic plants in such a way that:

- The amounts of wastewater produced and the pollutants content of the wastewater are minimised;
- Constituents of the baths can be recovered;
- Non-reusable waste can be recycled by other companies and sectors.

ZERMEG specifically wants to assist in the identification of all measures that have the potential to reduce waste and emissions from a process, and are economically feasible at the same time.

Now, two optimisation approaches can be chosen: The first one was published by Fresner [15]. The first step towards improving water efficiency in a galvanising plant involves a thorough analysis of the consumption of water and chemicals in the various process steps. These data could be derived from accounting data, such as the amounts of chemicals bought, or from on-site measurements and asking people who work with the equipment. All incoming and outgoing material flows should be recorded in as much detail as possible. If the company being analysed has an adequate environmental management system and employees with a background in doing mass and energy balances, these figures are relatively easy to find, otherwise it may take a while to obtain the necessary data.

In order to calculate specific indicators for benchmarking it is necessary to record the surface area per part and the throughput of parts per unit time. Data on the surface related consumption of water and chemicals are essential instruments for the localisation of measures to reduce consumption. Surface area can be measured from the geometric dimensions of the parts, calculated from their weight, or calculated from the electric current in electroplating processes [16].

The rinse criteria are defined as the ratio of the concentration of salts in the active baths over the concentration of salts in the respective final rinsing water. The actual rinse criteria are determined from measurements of the concentration of salts in the dragged out solution and the final concentration of the same salts in the last rinsing step in the plant.

To determine the ideal rinse criteria, the suppliers of the chemicals used in the baths are asked for the optimum concentration of the adhering liquid film on the work pieces after the last rinse step before the respective bath.

The ideal water consumption can be calculated using the compilation of formulae for the water consumption of a static rinsing tank, spray rinse, and two and three step counter current rinsing cascades of Nagy [16] for the feasible configuration of rinsing tanks in the plant. These data can be the reference for benchmarking [17]. Surface related data about consumption and the concentrations of chemicals are important indicators upon which optimisation approaches may be built. The ideal drag out for a given geometry is calculated according to the method of Kimmerl [18]. There will always be a variation in the parts to be coated, the drag out must be calculated for the different parts individually and then integrated according to the surface contribution of the individual parts. The ideal water consumption is then the minimum of the water consumption to reach a given rinsing criterion with the feasible configurations of rinsing tanks including the addition of rinsing stages, depending on space and cranes.

The ideal consumption of chemicals in the active baths is calculated from the ideal minimum drag outs and the models for the chemical reactions being used in the process.

This first strategy was applied to five galvanic plants with different processes (wire production, printed circuit board production, hot-dip galvanising, anodising and the production of printing cylinders).

The rinsing technology used by the wire producer was changed by the following measures:

- Combination of a two-stage rinsing cascade with a static tank to form a three-stage rinsing cascade;
- Separation of the rinses in the continuous pickling plants into three-stage rinsing cascades

The volume of rinsing water in the static pickling has already been reduced by 50%. At the same time, a theoretical approach that should allow the spent acids to be used in another company has been developed in recent months.

Two improvements were implemented at the printed circuit board manufacturers:

- An electrolysis plant to recover copper from etching concentrates and rinsing water;
- Use of caustic stripping solutions to neutralise acid concentrates.

This company was able to acquire a practically new used electrolysis plant. The feasibility study showed that the plant should definitely be installed. Because of capacity issues, however, the electrolysis plant was not installed at the location which participated in the project, but at a sister plant, which now recycles 20 kg of copper from the wastewater each day. The wastewater treatment plant now uses caustic concentrates after filtration to neutralise acidic concentrates. This saves 20 tons of caustic soda and a similar volume of hydrochloric acid a year.

At the hot-dip zincing plant, a consistently separated management of pickling tanks was introduced by completely separating the dezincing and pickling operations. They are currently recycled completely by two other companies. The topping up of the pickling baths is done on the basis of monthly bath analyses and consistent application of the mixing rules. This has reduced the acid consumption in 2004 by 50% compared to 2003.

In the anodising company, the direct evaporation of the rinsing water offered a good opportunity to install a complete rinsing water cycle. No organic compounds were found in the distillate, and its salts content is very low. This process should be implemented, if there is enough space for a third stage in the two rinsing cascades.

At the printing cylinder manufacturer, the galvanising machines were equipped with new flat nozzles with an optimised geometry, and water pressure was minimised. This reduced the water consumption by 50% and the acid consumption by 40%. The results are summarized in Table 6.

The implementations included measures which pay back in 0.5–3 years. Additional measures to further decrease the disposal of acids and caustics to the wastewater are technically feasible, but remain too expensive.

As an alternative approach to minimizing emissions from galvanising plants, a TRIZ based methodology was applied. In consecutive studies, as an alternative approach the TRIZ based Cleaner Production procedure was used (Austria Email, Austria Buntmetall, Omax, Orient, Union Steel). For each of the plants flow charts were drawn. The project teams consisted of the technical director, the environmental manager, and several operators. None of them had a chemical engineering background. For the process steps generating significant wastewater volumes, the technical elements of the problem and the functions in between them (useful and harmful functions) were identified (comparable to Fig. 3). Using this as a basis, in brainstorming sessions within the project teams within the company, the ideal final result was identified and the trimming questions were applied using the questions from Table 5 (third column). After this data regarding exact quantities and cost were generated to facilitate a feasibility analysis.

The results of this qualitative approach in these five plants were comparable to the results arrived at earlier by the more quantitative approach:

- In the continuous pickling line at Union steel the specific water consumption was reduced by 25% by cascading water in rinses
- In Orient and Omax by optimised rinsing water control by measuring conductivity consumption the water was reduced by 30%
- In Austria Email a combination of these measures yielded a decrease of specific water consumption of more than 50% (rinsing water cascade, automatic control of water flow)
- In Austria Buntmetall increasing the pressure of spray rinses and recycling of water resulted in a reduction of more than 50%.

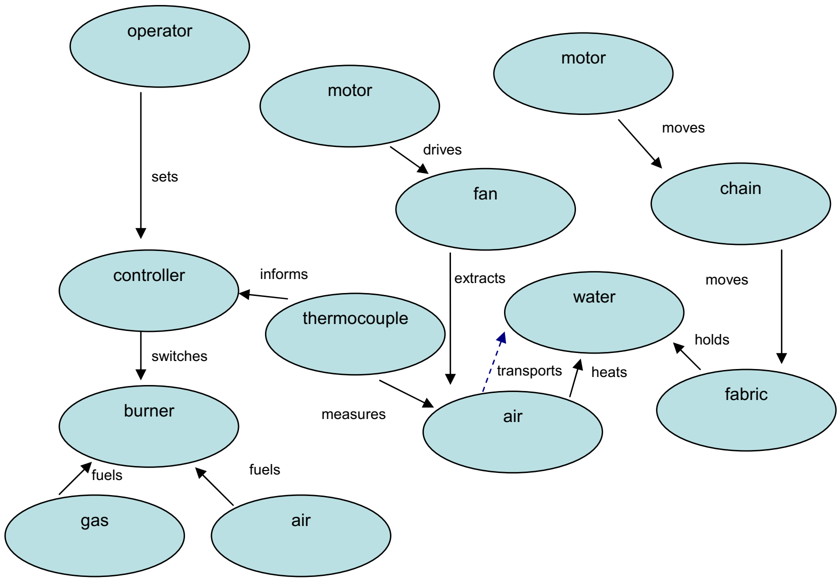

Fig. 3. Function analysis of the drying process in a tenter (dotted line: useful function, full lines: harmful functions, no waste or elements of the super system included).

4. Case study: ZERMET (Zero emission retrofitting for three existing textile plants)

Starting from 2008 on, the authors applied the TRIZ based Cleaner Production procedure to several textile mills in Austria (Fussenegger, Leichtfried, Baumann), within the ZERMET project, which again was funded by the FFG. The main goal of ZERMET was to proof the transferability of the TRIZ based ZERMEG approach to a second sector.

Initially, a flowchart was drawn for the processes in each of these mills. These flow charts were used to identify sources of wastewater and energy emissions. Then together with the project teams in the companies, priorities were assigned. Consequently, detailed analyses were conducted for priority areas.

Table 6
Summary of the ZERMEG results in the first five case studies using benchmarking to identify the ideal final result.

Company	Reduction of specific water consumption	Reduction of specific consumption of pickling medium (acid, caustic soda)	Other
Anodisieranstalt Heuberger	95%	50%	
AT&S	[a]	[b]	Recovery of 20 kg/d copper, savings of 20 tons/year of caustic soda, external use of sludge
Joh. Pengg AG	50%	[c]	Complete external use of spent acids planned
Mosdorfer GmbH	[d]	50%	Complete external use of spent acids achieved
Rotoform GmbH	40%	50%	

[a] Not relevant, because only the wastewater treatment was analysed.
[b] Not relevant, because only the wastewater treatment was analysed.
[c] Not yet analysed.
[d] No wastewater from rinsing, because rinses are used completely to make up pickling baths.

The case of a tenter is described in the following paragraphs. A tenter is a unit commonly used in textile plants to dry fabrics while preserving the desired shape of the fabric after washing and also for wet finishing (the application of aqueous solutions of resins and chemicals to the fabric which are fixated by drying afterwards).

A tenter consists of two parallel chains with needles, which hold the fabric. These chains guide the fabric to a dryer, up to 50 m long, which is heated to the process temperatures (80–150 °C) directly by gas, or by thermo oil or steam. Air is extracted from the tenter to remove humidity (and chemicals, which evaporate from the fabric).

Fig. 3 shows the function analysis for a tenter.

Looking at this analysis in two plants the following optimisation routes were identified:

The function analysis showed that in the tenter air is heated to transfer heat to the water which is contained in the fabric. At the same time some of this air is used to transport the humidity, therefore a continuous stream of air is extracted via a fan.

The ideal solution would be dry fabric without any harmful functions (costly use of energy, generation of waste heat in the exhaust air). Replacing the wet process at all was out of scope because of the specific requirements of the client.

The closest approach to the ideal final result could be realized by eliminating the water first mechanically by squeezing the fabric (not feasible because of the nature of the fibres). What is the next best solution?

Changing the drying mechanism to high frequency microwave drying, would eliminate the need for air for heat transfer and reducing its function to the transport of humidity. This approach was already applied in drying specific fibres in one of the mills. For the other applications, this idea was abandoned because of the high investment. What is the next best solution?

In the case of two companies, the motor was driving the fan at a constant speed, regardless whether they were drying heavy fabrics holding 200 g/m^2 of water or light ones with less than 70 g/m^2. This was pointed out during the discussion in the team while developing the function model. Measuring the humidity in the exhaust and controlling the volume of airflow accordingly was the approach that led to a 30% reduction in gas consumption.

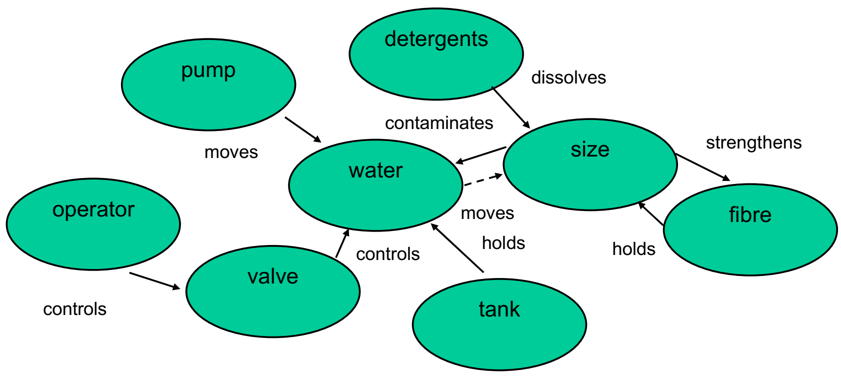

Fig. 4. Function analysis of the drying process in a tenter (dotted line: useful function, full lines: harmful functions, no waste or elements of the super system included).

Fig. 4 shows the function analysis for a washing process. Before weaving, size is applied to the yarn to strengthen it and to reduce friction. After weaving it has to be washed out of the fabric, because it would interfere with the consecutive wet finishing process. In the washing process, water and detergent is applied to solve the size. Rinsing water is used to rinse the dissolved size until the concentration of size in the fabric is below the maximum permissible concentration. The operator manually controls the water flow. During the discussion it was found that the water flow had been set for a worst case scenario of very heavy fabrics with a high concentration of sizes. Most of the fabrics actually contained a lot less size.

In this system, the use of size could not be changed. The company also did not want to change the chemicals used. The starting point for improvement was control of water: During the process of performing the function analysis it was discovered, that in the plant originally a conductivity control of the water flow had been installed. Because of technical problems it had been decommissioned years ago. The feasibility analysis showed that repairing it would save 35% of water consumption at a pay back of three months.

5. Conclusions

Analysing the strategies of cleaner production and comparing them to the Laws of Evolution from TRIZ has yielded a useful new interpretation of the strategies of Cleaner Production. The result is also a new convenient interpretation for explaining them in teaching. An effective approach to the minimisation of waste and emissions from industrial production processes is to conduct the following steps:

1. drawing of a flow sheet of material streams, auxiliary materials, water and energy, highlighting waste streams, wastewater generation, energy consumption and emissions, including auxiliary processes (like steam generation, air compression, water treatment)
2. performing a function analysis in the process steps where waste and emissions are generated
3. definition of ideality in these steps, applying trimming and backcasting intermediate solutions
   - select ideal raw materials (air, water, biogenic materials)
   - improve control of the process (documentation of key indicators, maintain optimum process conditions)
   - reduce human interaction by identifying possibilities for automatic control
   - improve the coordination of the production process with external requirements (also including recycling and passing function to the super system)
   - look for alternative technologies (following the principles of reduction of number of transformations, use counter current flows, use staged processes)
4. collect data on flows and monetary value of raw materials, energy and waste and evaluate the feasibility of the options.

This approach takes the ideal final result as a starting point for optimisation. This vision can serve as a long-term objective to focus the decisions about possible options for change towards the most useful ones, given the greater picture of the ideal feasible result. Because it is more qualitative and relies on less data it is apparently easier to apply, less time consuming than the usually applied mass and energy balance based approaches to implement Cleaner Production and it requires less detailed expert knowledge for the identification of options.

The TRIZ based approach is a valuable tool to moderate group work on developing CP options, also with team members with little engineering background. It does not require encyclopaedic knowledge of sector specific technologies. It is a systematic semantic approach to create powerful, though simple models for project steps, allowing to identify the origin of process inefficiencies. The approach also allows to expand the problem solving space beyond the original disciplines of the team members.

This approach is easy to explain to project groups in companies, because it starts analysis at a concrete function, which is not performed in the best possible way using simple, familiar language. This again leads to the search for physical and chemical effects which improve the situation supporting or even replacing encyclopaedic expert knowledge which otherwise would have been necessary to interpret the CP principles.

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