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Toward an eco-innovative method based on a better use of resources: application to chemical process preliminary design

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A B S T R A C T

Chemical industries have the potential to become a driving force to introduce efficient production practices for reducing the negative impact on the environment. In order to meet these environmental challenges, innovation is a key factor in turning the concept of green growth into a reality through the development of eco-friendly technologies and sustainable production. Therefore, to accelerate and improve the design of eco-inventive solutions, new approaches must be created and adapted to integrate the constraints of eco-invention in the preliminary design. The purpose of this paper is to present the first elements of a computer aided eco-innovation system to support the engineers in preliminary design. This research paper proposes a method based on a synergy between the Theory of Inventive Problem Solving (TRIZ) and the Case Based Reasoning. However, the typical level of abstraction of the TRIZ tools is modified. Indeed, TRIZ only gives way or guidelines to explore in order to find an inventive solution, which are often too abstract and hard to traduce into an inventive concept. To reduce this level of abstraction, this work proposes to apply the physical, chemical, biological, geometrical effects or phenomenon as solutions as they are more concrete. This is done thanks to a resources oriented search in order to better exploit the resources encompassed in the system. A case study on a new production process in chemical engineering illustrates the effectiveness of the proposed approach.

Keywords:
Eco inventive design
Eco design
TRIZ
Process system engineering

1. Introduction

1.1. Context

Manufacturing and chemical industries have the potential to become a driving force to introduce efficient production practices in order to reduce the negative impact on the environment. Their efforts to decrease this environmental impact have been moving from "end of pipe" technological solutions to limit or control pollution, to the integration of the environmental preoccupation in early stage of product or process design (preliminary design). To generate more integrated, efficient, and sustainable solutions the manufacturing and process industry implements solutions to minimize the material and energy streams by increasing the recycling; output as raw materials for another product or production process. This evolution has been detailed in the Organisation for Economic Co-operation Development (OECD, 2009) report, and summed up in Fig. 1.

To meet these environmental challenges, innovation is a key factor in turning the concept of green growth into reality through the development of eco-friendly technologies and sustainable production. In its reports OECD (2009) defines eco-innovation as "innovation that results in a reduction of environmental impact, no matter whether or not that effect is intended". In their paper (Santolaria et al., 2011) gave some explanations on how eco-design, and broad extent sustainability is connected to innovation driven companies.

In their strategies for sustainable practices, firms try to improve their production processes, their products but they are also more and more interested in the management of their products end of life and their waste. Indeed raw material and more generally all the resources will not be eternally exploited with an open loop approach, based on the input/output capacities of the environment. For instance in chemical engineering, the gradual depletion of hydrocarbon reserves, the scarcity of some resources will imply a decrease of the raw materials consumption and the transition to a circular economy. On this point, the waste management transitions from an environmental approach to an economical one: the waste is not only a constraint to minimize but also a resource to optimize leading to a circular economy. The chemical engineering has,

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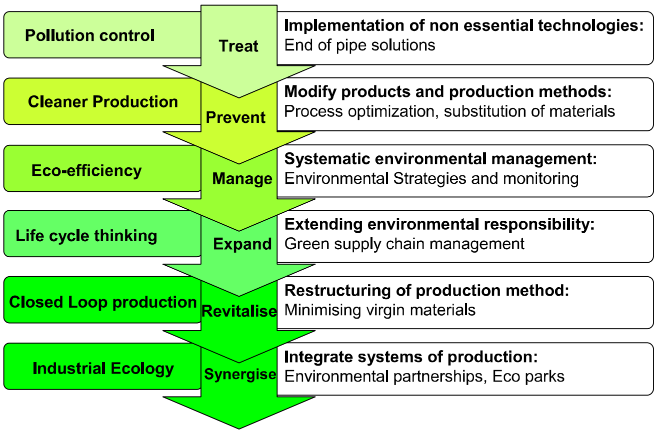

Fig. 1. Evolution of sustainable manufacturing practices, OECD (2009).

obviously an important role to play in so far as it uses resources, it produces waste. Consequently, chemical industry must innovate to find more eco-friendly products, processes but also to create processes for waste valorisation. In the same time, the process industries undergo, new trends imposed by the world market evolution: reduced time to market, decreased product life cycle. However in these industries, the development time for a new product or process is very long and still measured in years. Therefore chemical engineering needs design methods which able to accelerate innovation and to improve and optimize the use of resources in order to reduce the environmental impact of products and processes along their whole life cycle (from design to valorisation).

1.2. Knowledge based design methods

To accelerate its design process a company may use its knowledge capitalized in the past designs. Case Based Reasoning (CBR) is one of the most powerful artificial intelligence methods for formalizing, storing and reusing firms' knowledge. CBR is the process of solving new problems based on the solutions of similar past problems. It has been argued that case based reasoning is not only a powerful method for computer reasoning, but also a pervasive behaviour in everyday human problem solving; or, more radically, that all reasoning is based on past cases personally experienced. But to capitalize design knowledge it must have some repetition in the design activity. This recurrence in the design of systems requires little changes but is less obvious when dealing with innovation. Consequently, CBR deals with eco-design and not with eco-inventive design because it has a weak ability to innovate but can reach solution with a low level of inventiveness corresponding to incremental innovation. In their work (Wu et al., 2008) improved the CBR methods to propose a higher ratio of valuable product ideas but the level of inventiveness is still low. Gupta and Veerakamolmal (2000) and Veerakamolmal and Gupta (2002) applied CBR to eco-design for building a disassembly strategy. Shih et al. (2006) used the CBR to define a recycling strategy for products.

Consequently to propose innovation with a higher level of inventiveness, designers must apply specific methods dealing with creativity enhancement. Current computer aided innovation methods and tools are partially inspired by them as underlined by Leon (2009). Srinivasan and Kraslawski (2006) classified these methods into two main categories: analytical or intuitive methods. The latter searches solutions using randomized process because they do not have a formalized logical structure and among them; brainstorming, lateral thinking, mind mapping are most common. They lead to many iterations to generate a solution, thus a waste of time, money and human resources. In these methods the creativity process is composed of two successive logics of actions: first divergence which is followed by convergence. During the divergent part, engineers generate randomly as many ideas as possible along many directions. Because it is not conceivable to consider all these ideas for further design, the convergent part tries to manage them by merging some of them or by eliminating the less promising solutions using a multi criteria decision but with a high risk to loose very promising concepts. Jones et al. (2001) developed a product idea tree diagram for eco-innovation to structure outputs from chaotic idea generating sessions. Bocken et al. (2011) proposed a tool to facilitate the generation of radical product or process ideas for reductions of greenhouse gas emissions.

In contrast, the analytical methods partially withdraw the previous issue by proposing well-structured methods like morphological analysis or the Theory of Inventive Problem Solving (TRIZ is the Russian acronym). In (TRIZ) the creativity process is converging only because it postulates that no matter the number of concepts generated quality prevails, i.e. viability of the concepts. TRIZ is different from other inventive methods because it operates through generic models and not through the spontaneous creativity of individuals that is why it is widely used by industries and research community. It encompasses methods and tools to propose inventive solutions for not typical problems, and helps corporations and individuals to reach their peak potential.

To conclude, on the one side there are artificial intelligence methods that help to accelerate design thanks to knowledge capitalization through a case base but at the loss of the inventive aspect. On the other side, there are inventive problem solving methods which require a long time to reach a solution because each new design starts from scratch. However there is a lack of information and research on production process oriented approach.

1.3. Eco-inventive design methods

There is a broad diversity of eco-innovation approaches, Carillo-Hermosilla et al. (2010) presented an analytical framework to explore the diversity of eco-innovations according to several key dimensions. This research work focuses only on the design dimension. To support and improve eco-inventive design, several new approaches appear in the research literature. In these approaches, environmental aspects are integrated at the same level as the classical design factors. Most of these approaches and tools are product oriented for the development of functional solutions like in (Li and Huang, 2009), or environmentally or conscious product design by integrating product recovery (disassembly, recycling…) as the research conducted by Ilgin and Gupta (2010). However, there is no production process oriented approach.

In their approach (Cascini et al., 2011) aimed to bridge systematic invention practice with product life cycle management systems by integrating (TRIZ) principles within a computer aided design system. Concerning eco-invention, Fresner et al. (2010) applied (TRIZ) in cleaner production to have a more rational use of materials and energy to reduce waste and emissions in industrial activities. Chang and Chen (2004) conceived an approach based on the technical contradiction of (TRIZ) theory associated with eco-efficiency axes, proposed by Desimone and Popoff (1997), by defining a relationship between both. Their 5 steps process covers a part of the eco-inventive design process; from the problem formulation to the choice of the first design parameters. The main advantage of this method is in the first step with the choice of the eco-efficiency axes with respect to the design problem faced. However, the weaknesses are: the choice of the engineering parameter to improve (among the 39 of (TRIZ), detailed in part 2) is arbitrary, and, is still fuzzy around the technical contradictions. The four steps process of Kobayashi (2006) searched to improve the ratio of the "product value" compared to its "environmental impact" (calculated by a Life Cycle Analysis). For the generation of eco-friendly concepts the author coupled quality function deployment tools with an eco-specification matrix and the (TRIZ) matrix. In this approach, the (TRIZ) tools must be further adapted and integrated to the proposed process resolution. Indeed, there is only one engineering parameter of (TRIZ) associated to each eco-specification, not always justified. Sakao (2007) proposed another extension, coupling TRIZ and quality function deployment by integrating life cycle analysis. In another research Grote et al. (2007) presented, a methodology based on TRIZ, design for X tools and life cycle analysis to develop an eco-inventive methodology. In these methods, life cycle analysis is used to assess the environmental impact. More recently, Yang and Chen (submitted for publication) presented an approach based on the coupling between (TRIZ) and Case Based Reasoning (CBR). In a complementary research they enlarged their approach by adding life cycle analysis to the previous coupling (Yang and Chen, 2011). Their solving tool is based on the coupling between the (TRIZ) contradiction matrix and the seven eco-efficiency axes proposed by the World Business Council of Sustainable Development (WBCSD). Its main advantage it is easier to use for designers and (TRIZ) non-expert. Vezzetti et al. (2011) presented another approach based on (TRIZ) to support knowledge codification and knowledge management for the problem of waste disposal.

In their study, Samet et al. (2010) conducted a research on another way to integrate the WBSCD axis in the eco-innovation process and they present an evolution of their design tool to support innovation (based on (TRIZ) tools) to deal with eco-innovation problems.

This literature analysis puts in highlight that (TRIZ) is widely used in eco-innovative design approach (common denominator between previous studies) because it is probably the more appropriated approach to generate real technological breakthroughs. It offers a framework with various methods and tools to model and solve design problems. But these methods must be integrated in an eco-inventive approach and adapted to deal with eco-design constraints as done in the various studies cited above. Besides, they also need to be adapted to fit the increasing complexity of current designs. These interesting approaches are only focused on product design but the production process is also necessary to take into consideration. Furthermore, they have incorporated the major drawback of (TRIZ), i.e., its level of abstraction. Indeed, they give only ways or guidelines to explore in order to find an inventive solution, which are often too abstract and hard to translate into a concrete inventive concept. Another important drawback is that resources are never taken into account at the resolution step. This is awkward in eco-inventive design.

1.4. Purposes of the paper

In this context, to accelerate and improve the design of eco-inventive solutions, new approaches and methodologies must be created and adapted to integrate the various constraints of eco-invention in the preliminary design, with the purpose to guarantee and leverage the maximum environmental benefits. These new preventive approaches aim to eco-inventive technologies to reduce or eliminate the root cause of pollution instead of treating pollutants already produced.

The purpose of this paper is to accelerate the preliminary eco-inventive design thanks to a computer aided eco-innovation tool that is based on a better utilization of the resources. Computer aided innovation is a new domain in the array of computer aided technologies in order to answer to greater industry demand for reliability in new products or processes. Leon (2009) gave an analysis of the present status and the future of these emerging tools. Our goal is to introduce the environmental issue in our computer aided innovation tool. This computer aided eco-innovation tool focuses on assisting designers in the early stage of design and more particularly in the creative stage and later, provides help in order to generate eco-inventions.

Our first purpose is to ameliorate and adapt the current (TRIZ) tools in order to avoid three previous drawbacks when dealing with eco-invention, i.e. integration of eco-inventive aspects, evolution to deal with the growing complexity of current design and more importantly eco-innovation design, and decrease the level of abstraction of the proposed solution. Furthermore, the resources must be clearly integrated in the methodology because they are responsible to the environmental impact of the designed system. Even if (TRIZ) is implemented in some computer aided innovation tools, the development time of an inventive concept remains important. Consequently, the ultimate goal is to accelerate the time of development of eco-invention by implementing a synergy between the modified (TRIZ) tools and CBR. The remainder of this article is structured as follows. In Section 2, our previous methodology based on a synergy between (TRIZ) and CBR is introduced. Section 3 addresses the presentation of our eco-inventive method with a discussion on the use of the resources. Before to draw a conclusion and give some perspectives for future researches, Section 4 is dedicated to an illustrative example of our model by improving a chemical engineering process.

2. Synergy between TRIZ and CBR

2.1. CBR

Unlike many methods in artificial intelligence, CBR is memory based, reflecting human use of remembered specific problems and their solutions as a starting point for a new problem solving. The CBR approach tries to propose a solution for a problem by establishing some similarities with problems previously solved (i.e. cases) and stored in a memory (case base). As explained by Schank (1982) and Kolodner (1993), the main principle of CBR is: similar problems have similar solutions. Solving a problem by CBR implies, representing the problem, measuring the similarity of the problem faced to previous ones store in the case base, retrieving a relevant case and attempting to reuse the past solution of the retrieved case (most of the time with an adaptation step to account for the discrepancies in problem description).

In CBR, the central notion is a case which is a contextualised piece of knowledge representing an earlier experience that can be structured in accordance with the CBR purpose. Several models are available to represent the CBR process; nevertheless there is a general acceptance of R^5 model found by Finnie and Sun (2003), Fig. 2.

- Retrieve: It is the process for extracting, within the case base, the cases (source cases) that are the closest to the current problem. Here, the central issue is the similarity measurement which allows to determine how a case is appropriate for solving the initial problem. Due to its crucial impact on the whole CBR process, a considerable amount of research (Lopez de Mantaras et al., 2006) focused on retrieval and similarity assessment. Similarity is often measured by a mathematical distance between two cases with the common assumption that retrieval distance is proportional to the adaptation distance. However several authors (Smyth and Kean, 1998) questioned this assumption because the most similar case is not necessarily the easier to adapt and the most relevant for solving the

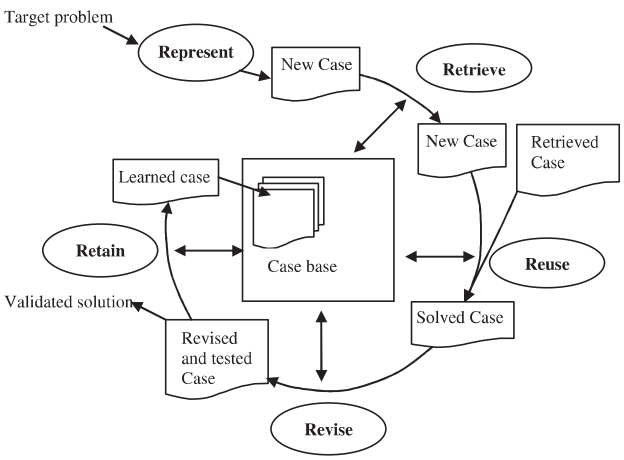

Fig. 2. CBR R^5 cylce.

problem faced. Riesco et al. (2010) conducted a research to improve the retrieval thanks to a new search algorithm and a criterion to measure the adaptability of a case.

- Reuse: The goal of this step is to propose a solution derived from the solution of the retrieved case (s) (source solution). Most of the time, there is a gap between the problems; therefore the source solution needs to be adapted.
- Revise: After adaptation, the proposed solution is tested (for instance by simulation or by experimental validations), to verify its adequacy and relevance with respect to the target problem, and also to consider what actions are to be taken to withdraw the remaining discrepancies.
- Retain: If relevant, the CBR system learns this new problem solving episode and therefore increases the CBR effectiveness by enlarging experiences retained.

This R^5 model is more complex and deeper than this current presentation because, each step involves number of more specific sub-processes with their own difficulties. A more detailed description is given in Lopez de Mantaras et al. (2006) and Pal and Shiu (2004).

Even if this approach has a learning step to extend the number of cases in the memory, it needs to gather a large number of cases, in order to cover a wide range of problems, to be effective and to have significant results. Among the many advantages of the CBR which can be underlined: its reduce knowledge acquisition task, its flexibility in knowledge modelling, its ability to support long term learning, its capacity for reasoning with incomplete or imprecise data, its vicinity to human reasoning and its rapidity to create and to maintain a computer decision support tool for designers.

Accordingly, CBR is clearly related to research in analogical reasoning, which is a domain of research in cognitive science. Analogical reasoning research focuses on methods of processing information and mechanisms that compare the similarities between new and previous understood situations (thanks to other cognitive process). However CBR has roots not only on cognitive science but also in various other disciplines, such as, knowledge representation, machine learning and mathematics (Richter and Aamodt, 2006 for a discussion on that topic).

But compared to analogical reasoning research, CBR often focuses on creating systems to perform specific task (scheduling, design, decision support&) where some level of performance is expected. Consequently, the knowledge capitalized is very specific in order to produce concrete and applicable solutions. In contrast analogical reasoning research tries to find universal representation. It considers that the processes are broadly general cognitive processes, as underlined by Lopez de Mantaras et al. (2006).

2.2. TRIZ

(TRIZ) is based on scientific observations and on extensive analysis of invariant design strategies applied across technical domains. To develop his theory, Altshuller (1996) analysed several thousands of patents, the evolution of technical systems and the scientific discoveries. He focussed his attention on the specific approaches and the processes followed by the inventors instead of on the system. After collecting and reorganizing information contained in patents, Altshuller tried to reformulate the problem in order to identify the technical barriers, how it was solved and the level of inventiveness of the proposed solution. Then, he built models that ignored the technical field of discovery in order to facilitate the transfer to other technical fields. Consequently, (TRIZ) is often presented as the reformulation of a concrete problem into an abstract one from the field of appearance. (TRIZ) methods and tools allow to moving from the abstract problem to a generic solution that should be adapted to the specific field. (TRIZ) supports the designer, helping to elaborate the abstract problem and to give access to knowledge bases leading to concepts of solution.

In his analysis Altshuller noticed that most of the patented inventions are transpositions or adaptations of technological or physical principles already known in a domain but implemented differently in another one (only les than 2% of discoveries are really new ones). As (Domb, 2000) explained, (TRIZ) is based on three axioms: technical systems do not evolve randomly but follow evolution patterns, behind each problem there is a contradiction to overcome and the problems must be solved according their specific conditions and the available resources. (TRIZ) gathers fundamental concepts and heuristics implemented in various methods and tools to analyse, model and solve complex problems. If the problem faced is standard the knowledge base with the "classical" (TRIZ) tools are sufficient as a first approach, left side of Fig. 3. In addition to these tools, an algorithm solver (ARIZ) was proposed by Altshuller for very complex problems. (ARIZ) structures the progressive application of the various (TRIZ) tools, right part of Fig. 3. Because of its use in our methodology, the contradiction matrix is presented as an illustrative example of the (TRIZ) philosophy.

Rather than solving a problem directly, (TRIZ) requires a reformulation step e.g. in the form of a technical contradiction (generic problem). A contradiction occurs when two opposite requirements

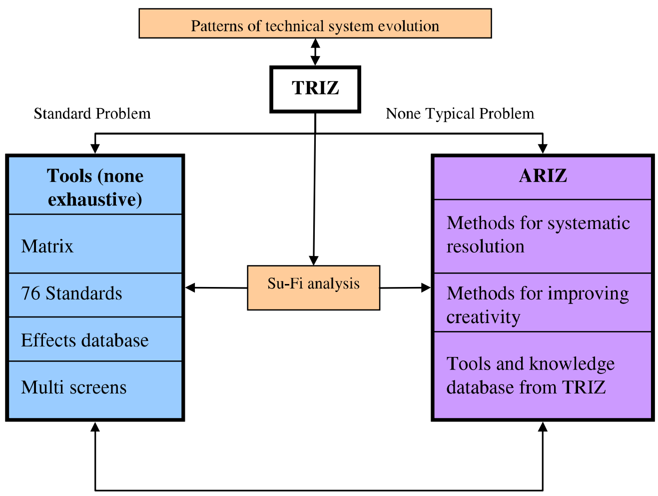

Fig. 3. Structural diagram of (TRIZ) (Livotov, 2001).

in a system must be associated to reach the design goal without a trade-off. During patents analysis Altshuller identified 39 engineering parameters that are the root of the technical contradictions. A technical contradiction expresses an incompatibility between 2 of the 39 engineering parameters: the first one represents the parameter that must be improved and the second one represents the parameter, that gets damaged, i.e., that impedes or obstructs improvement or the does not enable implementation.

During the search of solution invariants, the analysis had also allowed to extract 40 principles of resolution. Each one is a generic suggestion, a guideline to inventively solve a problem.

The matrix is the (TRIZ) tool that links contradictions to principles. This matrix is composed of 39 lines and 39 columns. On the former the improved engineering parameter, on the latter the damaged one. The crossing cell between the previous line and row isolates 3 or 4 principles. In each cell of the matrix, the principles assignment is based on a statistical study of the most frequently ones, used by inventors in the past to successfully solve the identified contradiction. Consequently the ranking of the principles expresses a recommended order of use. Once the most promising principle is identified, the designer must interpret and translate it into an operational solution; this last step asks for a creative effort. Fig. 4 illustrates how to use the matrix.

However (TRIZ) is not a black box where ideas are the raw materials and that would systematically produce an invention. (TRIZ) aims to systematize the conditions to impel the invention process by offering a set of concepts, tools and scientific knowledge. It supports designer to focus their attention to the most promising way of solution for a class of problems.

Because of its strength (TRIZ) leads to significant achievements, many successes and real technological breakthroughs in various companies. Among its strengths, its structuring, its scientific knowledge and its technological roots, are the most obvious. Besides, its systemic approach which takes into account the interdependence of systems and fluxes along the scales of time and space is well suited to address the current design difficulties.

However, many engineers have found with difficulties when they tried to apply (TRIZ) to their problems. First, the guidelines are too generic (e.g. the principles) because designers need more accurate solutions to their specific problems. Here a contradiction appears: the principles must be as generic as possible to be applicable in all the technological fields, whereas problems require concrete solutions. (TRIZ) has some other limitations for instance: its lack of methods, to analyse, to clearly identify, to extract and to reformulate a technical contradiction and its impossibility to solve simultaneously several contradictions. Indeed, with the increasing complexity of the current problem it becomes difficult to reduce the problem formulation to one and only one contradiction. In this condition, they must be solved sequentially. This is not satisfactory to obtain a more integrated and coherent solution and to decreases the resolution time (iterations). As a conclusion (TRIZ) must be adapted to current complex problems which ask for a wide range of human skills.

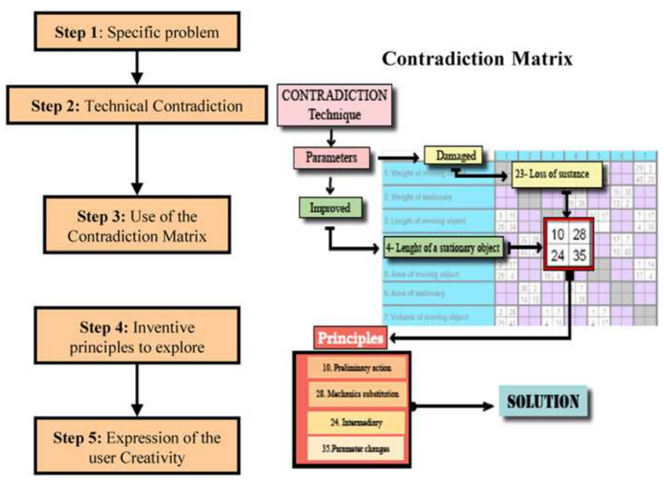

Fig. 4. Removal of a contradiction with the matrix.

2.3. Interest of the coupling

Before, to detail the synergy based on the complementarities between both approaches, a comparison is drawn up in Table 1. Both approaches are based on the analogical reasoning and exploit a knowledge base of past experiences. These two major points are the source of the coupling since these approaches use the same way of reasoning. Nevertheless, the main difference is the level of abstraction of the knowledge management. On one side Zha and Du (2006) explained that there is a highly abstract theory that categorizes existing knowledge into a series of design principles, rationales and constraints e.g. (TRIZ). On the other side CBR represents a collection of design knowledge into a certain case for description. Indeed, the premise of CBR is that a new design is relatively close to a past one. Consequently, CBR is well suited for routine design but limits creativity, fundamental component of inventive design. Therefore, the change in the level of reasoning is the source of inventiveness because engineers use knowledge coming from another scientific field. Altshuller (1996) clearly demonstrated, that, the level of inventiveness of solutions is closely related to the transfer of knowledge through technological domains.

Thanks to its memory, CBR can propose a solution rapidly without restarting the design process from scratch. In (TRIZ), the absence of memory compels the designer to do a thorough analysis to determine the conflict and the relevant tool to use, which is time consuming.

As Cavallucci et al. (2010) underlined another important difference lies in the direction of research. In CBR, it is imposed by a short-term vision that tries to improve existing systems either by analysis of its limits or by new customer requirements. In the opposite, in (TRIZ) the direction of research is based on technological evolution patterns, thus not imposed by a strategic vision.

Yang and Chen (submitted for publication) also proposed a coupling between both approaches. In their approach the (TRIZ) theory is included in the adaptation stage of the CBR. They have

Table 1
A comparison between CBR and TRIZ (Cortes Robles et al., 2009).

	CBR	TRIZ
Similarities	Analogical reasoning Exploitation of a knowledge base Reference to past design problems	
Differences	Knowledge inside a specific field	Inter field knowledge (transfer from one field to another)
	Searches of solution based on various orientations: customer requirements	Searches of solution based on evolution patterns
	Solves relatively close problem	Solves any types of problem
	Propose routine concept	Propose inventive concept
	Proposes rapidly a solution without starting from scratch. Relies on past design to elaborate a partial or complete proposition of solution	Important analysis of the problem to determine the conflict.
	Has a memory for success or failure	Does not have memory

modified the CBR cycle to include an eco-inventive design during the reuse step in order to propose inventive solutions. The eco-efficiency axes are used as an eco-design target. Furthermore, in their resolution process, the first stage on new product design information is not clearly explained, they do not detail how the problem is represented, but it is a crucial step for resolution in the next process in particular. In their tool the engineering parameters of (TRIZ) are linked with the eco-efficiency axes thanks to a statistical analysis of the (TRIZ) matrix but these links are not exhaustive and not always justified. They have built a relation table based on associations between engineering parameters and inventive principles (number of times a principle is associated with a parameter whether it is damaged or improved). With this relation table, designers can select related engineering parameters under a certain eco-efficiency parameter. Finally, designers use the classical contradiction matrix in its original form with the 40 principles to overcome the eco-inventive design problem.

One of the main difficulties of their approach is to find the engineering parameter which is coherent with the eco-efficiency axes and the design purpose. Besides, the idea of performing their statistical analysis sounds inappropriate because:

- some principles that are never used (e.g. principle of "equipotentiality") can be useful to guide designers towards eco-friendly solutions.
- the same inventive principle should be interpreted differently according to the specific contradiction identified. Consequently, the statistical analysis should include the meaning of the contradiction and the interpretation of the principles which is not the case.

This research work proposes a more integrated approach with a stronger coupling between the two previous methods.

2.4. The synergy

In this combined approach, (TRIZ) provides the generic knowledge and the initial structure to generate case indexation. CBR brings techniques to compare and search among previously solved problem. Thus this coupling is a way to add a memory to (TRIZ) for the capitalization of new solved cases in inventive design. This synergy combines two types of knowledge: generic from various fields using (TRIZ) and domain specific through capitalization.

In its initial form (firstly presented in Cortes Robles et al. (2004)), the features describing the problem part of a case are composed of: the contradiction, information about the problem environment, the objective of the research, the final ideal result ((TRIZ) concept not presented here), available resources in the system and its environment. The solution section gathers the principles used to reach the solution, a description of the solution concept and a description of the concrete implementation of the solution (it includes advises, information for new possible applications…). All these aspects are detailed in Cortes Robles et al. (2009).

The resolution of the problem follows the process presented on Fig. 5. It starts with an analysis of the problem in order to fill all the features for its description. After this problem formulation step, the user has two possibilities:

- To search a similar case in the memory. The matrix is used to index cases because problem formulated with the same contradiction are solved with the application of the same principles (interpreted according to the contradiction) therefore they are very close and can be stored in the same subspace. If a relevant case is retrieved then its associated solution is evaluated then adapted. If no similar case is retrieved then it should proceed to the next step.
- To use the matrix in its initial application with the use of the principles. The user can choose to jump directly to this step without going through the retrieval step.

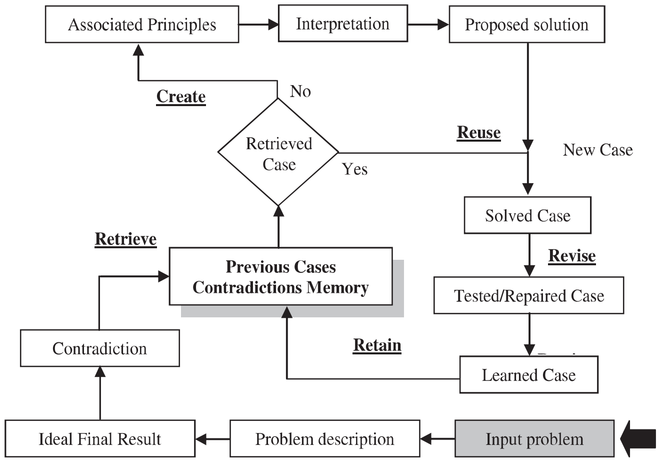

Fig. 5. Resolution process in CBR-TRIZ synergy.

Whatever the choice the process converges to a concept of solution which can be modified, adapted and validated in order to create a new case. This new case can be retained to enlarge the case base.

2.5. Discussion

Built with the aim to make more applicable, the guidelines of solution proposed by (TRIZ) and to accelerate the design, implementation of such a synergy brings several questions. Indeed, Estevez et al. (2006) demonstrated that it is neither a use of CBR in inventive design nor the original logic of (TRIZ). Moreover the retrieval, which is realized in a specific scientific field, limits the generation of new knowledge necessary for inventive design. Three answers can justify the synergy.

First, the scope of chemical engineering is very wide, with range of disciplines (materials, chemical, mechanical…) and phenomena involved in many devices. The proposed approach allows the exchange of knowledge between disciplines while remaining within the process engineering. It offers the possibility to create new knowledge with a limited scope but useful for the generation of concept with a medium level of inventiveness. With current developments in process engineering (miniaturization, intensification of the phenomena, the openness to biotechnology), this tool facilitates the transfer of technological solutions avoiding some pitfalls, thanks to information on the implemented solution.

The tool built on this approach facilitates the handling of (TRIZ) and its insertion in the industrial world. One difficulty for applying (TRIZ) is the significant effort of interpretation needed during the transition from the abstract principle into a concrete solution. It is therefore fundamental to increase the applicability of techniques and tools of (TRIZ). With the proposed examples of interpretation of the principles under similar conditions across domain, it provides insight into the transition.

In order to take advantage after implementing a solution, the knowledge stored in the system could be useful in two ways: in the early design stages (preliminary design) or as a criterion for evaluating the pertinence of proposed concepts or ideas. Cavallucci et al. (2010) suggested that it would be useful in the feasibility study phase of solution concepts. In such conditions cases are used to avoid past failures, and to justify or invalidate the relevance of some decisions.

Despite ameliorations for the creation of an effective tool for inventive design, some drawbacks still remain. First the level of abstraction is still too high and some guidelines are always difficult to transform into an operational solution. Moreover, the problem is still described with one contradiction which is very annoying with regard to the increasing complexity of systems. Furthermore, the specific design constraints are not included in the problem description. The next section proposes an evolution of the approach to deal with these drawbacks on one hand and to include environmental concerns in the problem formulation on the other hand.

3. Methodology for eco-inventive preliminary design

3.1. Matrix evolution

The classical (TRIZ) contradiction matrix must evolve to propose eco-inventive design. In their approach Chen and Liu (2001) examined how the seven eco-efficiency parameters of the WBSCD and the 39 engineering parameters of the contradiction matrix are related (detailed in part 2.3). The performance of their tool is strongly related to the coherence between the choice of the engineering parameter associated to eco-efficiency parameter and to the frequency of their association with principles. This frequency has nothing to do with the use in eco-invention because the matrix is built to solve technical contradiction, as also noted by Samet et al. (2010).

For a better specification and performance of the resolution method, the proposed approach of eco-invention consists to target more appropriately the principles with respect to the eco-efficiency parameters. Indeed, the eco-parameters are considered like engineering parameters and included in the matrix in order to formulate technological contradiction associated with the process or the product operations. As well as the engineering parameters, an improvement of an eco-efficiency parameter will express that the eco-process should improve its environmental impact. When it is damaged, a harmful parameter adversely impacts the environment. Consequently, the classical matrix is enlarged (46×46) to gather the new parameters, Fig. 6. For the newly established cells, the principles associated are researched among the 40 ones thanks to the study conducted by Chen and Liu (2001) and an additional

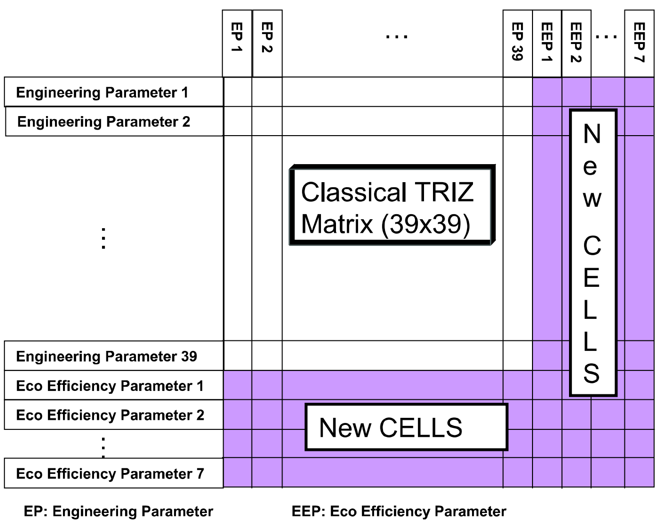

Fig. 6. Extented classical TRIZ matrix (46×46).

analysis of eco-inventive patents (coming from various patent databases and the WBSCD web site). The eco-efficiency parameters were revised and their definition enlarged to integrate them in the matrix:

- EEP1: Material Intensity
- EEP2: Energy Intensity
- EEP3: Dispersion of Materials or waves
- EEP4: Recyclability
- EEP5: Use of renewable resources
- EEP6: Durability
- EEP7: Service Intensity

It can be noticed, that these seven eco-parameters undoubtedly overlap the initial engineering parameters. EEP2 is the most obvious, because it is formed through the combination of the existing engineering parameters; 19 Energy spent by a moving object, 20 Energy spent by a non-moving object, 22 Waste of energy. Nevertheless, a detailed analysis of the matrix reveals that overlaps between the original 39 engineering parameters themselves also exist, but it was decided that it is more efficient to provide some specific parameters to clearly identify a contradiction. EEP2 falls into the category of meta-parameters because it gathers some existing ones but it has also a broader definition. It can be used when uncertainty still remains or when the system does not correspond to any engineering parameters.

3.2. Effects for solution

As mentioned above, (TRIZ) gathers several methods for modelling the problem with their associated databases for solving them. During the different steps of (ARIZ), the problem is represented with these various models. Nevertheless, there is neither an obvious link among different modelling approaches nor any kind of instructions to facilitate the transition between two of them. Although they give different glimpse of the system, it is quite difficult to use together the various problem representations without (TRIZ) expertise.

(TRIZ) proposes modelling approaches and knowledge bases with a decreasing level of abstraction. The lower the level of abstraction is, the deeper is, the problem analysis. Technical contradictions are at the higher level of abstraction, and then follow the physical contradictions and the substance–field analysis. With the physical contradiction, the problem is represented with one parameter of the system which must have two opposite and contradictory values, e.g. smooth and rough. They are solved with the separation principles. In the latest model, the problem is described thanks to an analysis of the substances, the physical fields and the interactions between them. The Substances Fields analysis directs the user towards two knowledge sources: the standards and the effects. As the Substances Fields analysis is closer to the physical reality, its associated resolution tools lead to concepts easier to evaluate compared to the abstract solutions given by the 40 principles.

On one side, the technical contradictions and the matrix offer a conceptually easy tool to use in the first approach, but it operates at a high level of abstraction. The concept of solution is too abstract and often needs to be transcribed and validated in the domain of application. On the other side, the Substances Fields analysis needs a deeper analysis of the problem and a deeper knowledge of the modelling approach but is based on sharper knowledge and allows generating concepts closer to concrete solutions. It would be interesting to combine the conceptual simplicity of the technical contradiction with the concrete ways of solution proposed by effects.

The physical, biological, chemical and geometrical effects help designers to transform ideas into concrete actions realized by the system. These scientific effects or phenomena are the base of all the material conversion, technological accomplishment and technical breakthroughs. Among the thousands of effects registered in the scientific literature only few of them are applied in industries (less than 400). Thus the introduction of new effects or the use of a known one in another context lead to new inventive ideas by using them in combination with resources not sufficiently or not previously exploited. These effects reveal to be an important source of knowledge for solving design problems.

Consequently, it would be interesting to link the effects with the principles. In a first phase, all the 40 principles were decomposed into more detailed and more concrete sub principles (between ten and fourteen for each one) thanks to a statistical analysis of the matrix and a patent analysis too. Then, a list of effects was associated to each sub principle. As the interpretation of the principle depends on the contradiction, the design goals and the specific conditions, for each principle there are several lists associated in accordance with the original technical contradiction. To be useful for problem resolution, effects do not have to be stored in alphabetic order as currently done in classical databases but must be ranked with respect to the functions to accomplish.

The use of effects requires an analysis of all the resources in the system and its environment. Nevertheless, in the Substances Fields analysis the designer focuses its attention only on the substances and the fields that are at the root of the problem. In an eco-inventive approach it is mandatory to integrate all the resources as specific conditions of the problem.

3.3. Resources constraints

The scientific effects require, unavoidably, the use of resources which must interact, in the space and time to ensure functions. Obviously the resources refer to materials. Because it is affected by mechanical factors, environmental impact and cost, selection of materials has been studied by several researchers. Giudice et al. (2005) proposed a method to reduce the environmental impact of selected material while satisfying functional and performance requirements. Tseng et al. (2008) added a cost analysis to the green materials selection. In contrast, Zhou et al. (2009) proposed a multi criteria method for material selection. However resources are not limited to materials in the approach it has a broader definition it encompasses the substances and their state (gas, liquid, solid, plasma…), the physical fields (e.g. chemical, mechanical, electrical…) and also time space, systems as illustrated on Fig. 7.

The time characterises, the time range before, during and after the achievement of the various functions. The space specifies, whether if some free areas are void, available or free in order to be exploited. The term resource, also encompasses, the system resources which refer to new functions or properties created by modification of the arrangement (links) between subsystems or by

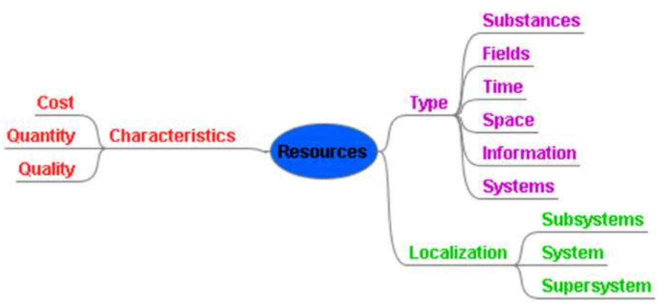

Fig. 7. Resources characterization.

a new way to link them. The resources by itself do not bring the desired function without interactions. Theses interactions must be characterized in terms of:

- Quantity: sufficient, insufficient, limited, unlimited…
- Quality: useful, harmful, neutral, waste, toxic, easy to recycle…
- Cost: free, expensive…

In the same way, it is important to localize these resources: in the system, the subsystems, the super system or its environment. This characterization of resources will be helpful to retrieve a relevant effect for the faced problem. It is important to note that this way to classify available resources in the system is a subjective measure, but strong enough to produce an initial rank.

3.4. Case description

In the proposed system a case has the same structure as presented in the section 2.4, i.e. problem description, solution and implementation advice. Here the problem is composed of the following features:

- Contradictions: The user can specify one or more contradiction (less than four). It can be useful for complex situation.
- Goal: In this part, the designer fills the aim of its research. It is traduced with an action verb.
- Resources: Unlike the Substances Fields analysis, in this features all the resources in the system and its environment are specified.

The solution part encompasses a list of effects in accordance with the problem description that can be used to find a solution. In the case of a multi contradiction problem, this list is reduced to the common effects between them. The implementation advice is the same as described in the previous section 2.4.

3.5. Solution retrieval

The cases representation and the similarity measurement for case retrieval are strongly linked. The goal of the similarity measurement is to establish the degree of similarity between the target problem and the source ones.

The problem faced (X) is compared with a source one (Y) by the way of the global similarity measurement (1):

$$\mathrm{SIM}\,(X,Y) = \frac{\sum_i w_i \mathrm{sim}\,(x_i, y_i)}{\sum_i w_i} \tag{1}$$

The similarity criterion allows to rank all the source cases from the most similar to the less similar. The global similarity calculation is reached by the weighted (w_i) sum of local similarities: sim (x_i, y_i). The former are used to express the relative importance between features. The user can set himself the weight values by assigning a value between 0 and 1, or it can be helped by asking him to classify the attributes according their order of importance. Attributes with rank 1 are the more important, and two attributes can have the same rank. For each feature, its corresponding weight is calculated by:

$$w_i = 1 - \frac{\mathrm{rank}_i - 1}{\mathrm{Max}\,(\mathrm{rank}_i)} \tag{2}$$

The local similarities are used to compute similarities between values of single attributes. They are calculated for each attribute (i) by comparison of the value of the target problem (x_i) with the corresponding source one (y_i). The local similarity between resources is calculated with a similarity tree that divides resources into classes and sub-classes. Then, a hierarchical structure is built to describe the relationship between classes (see Negny and Le Lann, 2008 for details on the method).

However, an effective retrieval must find a relevant case for the problem resolution. In its current form, the similarity measure based on a metric distance reaches its limit. Indeed, the similarity does not evaluate if a case is easily adaptable. The conventional similarity is often based on surface characteristics and must be extended to accommodate more sophisticated similarity assessments. This is done thanks an adaptability criteria.

3.6. *Adaptability of a retrieved solution*

The retrieval of a relevant case is the key milestone of the proposed approach. Consequently, the criterion to extract source case in the base is central and crucial step as it strongly influences the problem resolution. The success and efficacy of the approach depends on the retrieval of a source case that can be successfully adapted to propose a suitable solution. In this context the similarity measurement does not guarantee the usefulness and the utility of a retrieved case because the most similar case is not necessary the most appropriated for the adaptation purpose. Indeed, even if the similarity can be customized with the weights to refine the user research, it corresponds to a metric distance between two cases. Unfortunately, two problems can be very close but with a technological gap in their solutions. On the contrary, a case can be distant from the description of the problem but technologically its solution is more relevant and more easily adaptable to elaborate a new design solution.

In their research, Smyth and Kean (1998) found that it would be helpful to improve the similarity measurement with deeper knowledge about the significance of these features. They have introduced an adaptability criterion to evaluate the difficulty of adaptation: measures whether a retrieved source case can be easily modified to fit the initial problem. They called their technique "adaptation guided retrieval". In their approach, the appropriate adaptation knowledge is assumed available to be encoded with rules. Unfortunately adaptation knowledge has to be acquired but also be maintained which is a very long and difficult task. Besides, if this knowledge is incomplete the effectiveness of their method will degrade. In the proposed approach the adaptability is evaluated through a cost of adaptation that needs no additional knowledge to be encoded.

As eco-invention tries to encourage sustainable practices, a better use of resources and the introduction of renewable ones must be ensured. Moreover, the eco-inventive approach advocates effects or phenomenon to solve the problem, thus the adaptability depends on both the resources in the system and those required for the application of the retrieved effect. For each resource *j* needed to implement the retrieved effect a local adaptability is calculated by considering the characteristics and the localization of this resource in the system:

$$\mathrm{Ad}_j = \mathrm{Ad}_j^{\mathrm{Qt}} * \mathrm{Ad}_j^{\mathrm{Ql}} * \mathrm{Ad}_j^{\mathrm{Co}} * \mathrm{Ad}_j^{\mathrm{Lo}}$$

With $\mathrm{Ad}_j^{\mathrm{Qt}}$ the local adaptability of *j* based on the resource quantity, $\mathrm{Ad}_j^{\mathrm{Ql}}$ for the resource quality, $\mathrm{Ad}_j^{\mathrm{Co}}$ and $\mathrm{Ad}_j^{\mathrm{Lo}}$ for respectively its cost and localization. The local adaptability on the resource is calculated thanks to the values in Table 2. When a resource, useful for the effect implementation, is absent in the system and its environment its local adaptability is zero. But when it is present, the amount of the resource must be quantified to evaluate its adaptation easiness, i.e. the more the quantity, the more is easy to use. Concerning the quality, when the resource is already present but under the form of a waste or have a harmful action on the system, its recovery through functionality is very beneficial. Similarly, the use of a neutral or useless resource is interesting. On the contrary, when the resource needed is already encompassed in the system to achieve a function the value for its quality adaptability is assigned to the lowest value, i.e. 0.3. For the cost, the less expensive the resource is, the higher is its adaptability cost. When the required resource is already in the system, it is quite easy to use. On the other side when it is in a sub system or worse in the super system it must be brought to where the action will occur. This generates a new energy path with additional subsystems to transport the resource often resulting in a loss of performance.

Once the local adaptabilities evaluated for each resource, the global adaptability of the proposed effect is calculated:

$$\mathrm{Ad} = \sum_{\mathrm{j}=1}^{n+2} \mathrm{Ad_j}/(n+2)$$

Where *n* is the total number of substances and fields used by the effect, the two additional are the time and space. It is important to underline that there is an additional option for the adaptability calculation: when the total number of missing resources is greater than 3 (adjustable value) the global adaptability of the retrieved effect is 0. Indeed, the user can consider that the adding of more than 3 new resources in the system goes against an eco-inventive design. However this option can be disabled because the design of new eco-innovative systems can ask for new resources that are more sustainable or more easily recyclable. Finally, even if the design clamours for the introduction of several new resources the new system can be globally more eco-friendly.

Fig. 8 illustrates the four step proposed approach, each step is decomposed into sub-step. First, the problem formulation step is composed of; the contradictions identification (thanks to a specific tool not detailed here). The eco-efficiency parameters offer the possibility to formulate environmental issues. Then the user gives its design goals, and identifies all the resources in the system and its vicinity. In the retrieval step, the TRIZ-CBR approach search past experiences thanks to the new matrix and the case base. The most relevant source cases are extracted thanks to the similarity and adaptability measures and a specific search algorithm. This step encompasses the resources oriented search. In the third step, the tool proposed physical, chemical and biological effects as guidelines. The solutions of the most relevant source cases are also presented in order to give a concrete example of a past successful implementation. This step finishes with a creativity step where the user tries to find a specific solution to its initial problem by using the proposed effects. In the last step, the proposed solution is tested and adapted (iteration between these two steps) to completely match the initial problem requirements. Once solved, the new problem is stored in the case base and enlarged the tool effectiveness.

4. The simulated moving bed

4.1. *Scope of the study*

Chemical engineering deals with the production processes that convert raw materials into more useful or/and valuable products

Table 2
Parameters to calculate local adaptability.

$\mathrm{Ad}_j^{\mathrm{Qt}}$		$\mathrm{Ad}_j^{\mathrm{Ql}}$		$\mathrm{Ad}_j^{\mathrm{Co}}$		$\mathrm{Ad}_j^{\mathrm{Lo}}$	
Missing	0	Useful, easy to recycle	0.3	Very expensive	0.3	Super system	0.3
Insufficient	0.6	Useless neutral	0.6	Expensive	0.6	Subsystems	0.6
Sufficient	1	Waste, harmful, toxic	1	Free	1	System	1

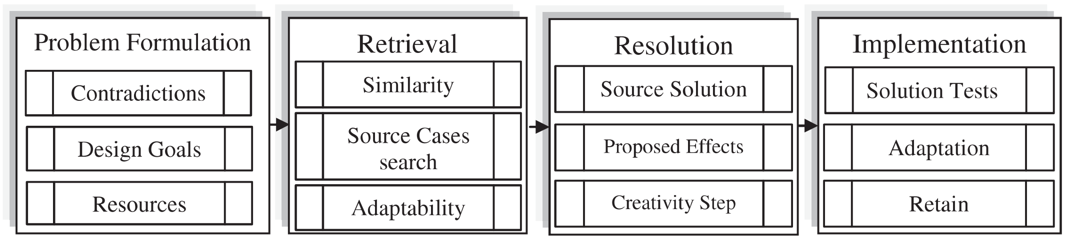

Fig. 8. Stepwise approach of the method.

through several transformations. Chemical engineers have to design process under economical, environmental, safety and energy constraints. A chemical process is composed of individual apparatus called unit operations: chemical reactor, separators, mixers… For the purpose of this case, units carrying out separation play an important role. The scope of the study is the combination of chemical reaction and separation, Fig. 9a.

The example deals with the reaction of methanol (Meth) and acetic acid (Ac) to produce methyl acetate (desired product, Meth Ac) and water (W). The conversion process is composed of a reaction step followed by a separation one. The productivity of such a process is low because the chemical reaction is an esterification which is a category of reaction limited by a thermodynamic equilibrium between reactants and products. This is a reversible reaction, i.e. at the beginning the products are formed and when the equilibrium is reached (enough product created), the products can react to give the initial components, consequently the total conversion of reactants can not be reached. After the reaction, the compounds are separated and reactants are recycled in the reactor. This implies a batch production and thus a small productivity.

There are numerous techniques to separate and purify chemical compounds. Among them, the simulated moving bed (SMB) is a chromatography technique for the continuous separation of multi components mixtures that are difficult to obtain using traditional separation techniques. This technique has recently been the center of attention of new research interest due to its wide application in new areas such as biological, pharmaceutical, fine chemistry or food industries. SMB is a practical evolution of the true moving bed (TMB), Fig. 9a. In TMB process, the mixture to separate is fed continuously in the column. Inside the column there is a counter current flow between a solid and a liquid phase. At the output of the column, both streams are recycled into the inlet to improve the separation efficiency. An eluent is also injected in order to facilitate the separation, i.e. to transfer more easily a compound from one phase to another. Two outlet product lines allow removal of products: extract (the compound is retained, more preferentially in the solid phase) and raffinate (rich in less retained compound). The principal drawback of the TMB was the motion of the solid phase. To eliminate this weakness, the SMB was created, Fig. 9b (the process is the same as Fig. 9a but the SMB replaces the TMB). It consists of column of uniform cross section with different length and packed with an absorbent. The columns are connected in series in a circular way. Two inlet streams and two outlet streams divide the system into four sections: S^1 desorption of the more retained component, S^2 desorption of the less retained component, S^3 adsorption of the more retained component and S^4 adsorption of the less retained component. It simulates the counter current movement by moving periodically (at predetermined time interval, i.e., switching time) and simultaneously inputs and outputs streams along series of the fixed columns. In SMB, the solid phase is static and the rotating motion simulates the fluid flows. In a previous paper Cortes Robles et al. (2009) explained how to find the SMB operating principle starting with the TMB process by applying the TRIZ-CBR synergy presented in part 2.4. Nevertheless it is necessary to go further by improving the SMB process.

4.2. Problem description

Concerning the process the principal goal to reach is to increase; the productivity, the purity of compounds after separation, the conversion, the flexibility and the process efficiency. For the environmental purpose, the consumption of energy and eluent must be decreased. The use of eluent is an important issue because classical eluents often have a high negative environmental impact on the one hand and requires a specific unit operation to regenerate them on the other hand. Currently, the research of green eluent is an important research topic in chemical and chemical engineering.

To go further in the problem modelling, a deep analysis of the problem must be conducted in order to extract the principal contradiction and to list all the resources available in the system and its vicinity.

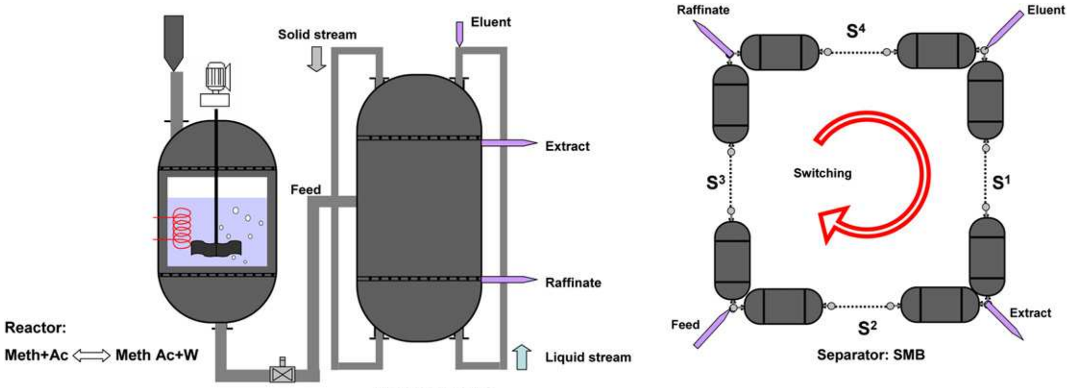

Fig. 9. a) Initial process, b) Schematic illustration of the SMB separation device.

After a detailed analysis to rank and prune the different sub problems, the global problem can be modelled with two remaining contradictions. One of the major weaknesses of the process for this reaction is its low productivity. Currently when the equilibrium is reached, the mixture must be separated and the unconverted reactants recycled in the reactor. One way to improve this productivity is to increase the temperature of the reaction to reach the equilibrium more rapidly. Indeed, the temperature elevation decreases the reaction time but unfortunately has no effect on the equilibrium. Esterifications are athermal reactions thus temperature has no influence on the composition at the equilibrium. The contradiction coming from the equilibrium issue is the following: Productivity (Improved engineering parameter) VS Energy Intensity (damaged eco-parameter).

The other main contradiction concerns the problem of raw materials. To accelerate the reaction, a solid catalyst must be introduced but it must be changed regularly because its activity decreases over time. It must be regenerated. Besides in the SMB process, the eluent consumption has a considerable effect on the environmental impact of the process but also on the effectiveness of the separation: purity of the constituents in the outlet streams and easiness to separate compounds. Thus when eluent consumption is increased, the environmental impact also gets increased and more effective is the separation process. The global problem of raw material (catalyst and eluent) can be summed up with the contradiction: Material Intensity (eco-parameter improved) VS Productivity (engineering parameter damaged).

Concerning the resources, Table 3, details some of the principal resources present in the reaction and the separation steps (the exhaustive list is too long to be detailed). For presentation simplicity the resources presentation in Table 3 is limited to the perimeter of the system but the same table was also set up for the super system.

4.3. SMB reactive

Based on similarity and adaptability, the retrieval steps in the methodology ranks in the first place the geometrical effect "Put several systems (or object) inside others". This effect suggests the idea to integrate the reaction and separation parts in the same device. This integration could enhance the conversion and the productivity of the process. Indeed, the products are separated as they are formed, the equilibrium shifts towards the desired product formation. This allows driving the reaction to the completion while recovering the compounds as on their production. Using a single apparatus for reaction and separation is in line with the process intensification, which is a potential way for the process improvement to meet the increasing demands for sustainable production. To combine reaction and separation in the same apparatus is one of the most important current challenges in chemical engineering, asking for real technological breakthroughs to intensify the phenomenon and to overcome the difficulties associated with this coupling. The use of this effect also leads to favourable operating conditions in order to reduce the environmental impact. First, thanks to the resources constraints the energy cost of the process can be reduced. Initially, it needs two thermal fields one for the reaction the other one for the separation part, by integrating the two unit operations, a thermal field can be eliminated thus greatly reducing the global energy consumption of the process. Second, as one objective of eco-inventive design is to decrease the use of materials; the two different solid materials considered in the initial process configuration may be restricted to a unique solid phase, having two features both catalysing the reaction and selectively sorbing some chemical components. Consequently, this process integration leads to a decrease of operating costs, an improvement of productivity and purity, but also to a minimization of raw materials (dual role of the solid phase and equilibrium shifting). Here, the SMB Reactive (SMBR) is obtained. The technical realisation of such a process is achieved by the use of a multiplicity of columns in series and a complex valve arrangement to provide the inlets and outlets at appropriate locations. Moreover, the coupling of reaction and separation in the same apparatus results in a continuous production. Indeed, previously the mixture to separate was sent to the separation only when the reaction was finished (batch production mode). With the SMBR, products are continuously produced and purified leading to an increased production by eliminating the transition time due to the filling and sewage phases of the reactor.

To go further in the process improvement, the other proposed effects are analysed. A physical effect ranked fourth according the similarity criteria but second under the adaptability one can be combined with the previous one. The new effect advocates to deliberately not synchronize the system. This effect leads to the proposition of the following idea to the process: the initial global shifting period in the SMBR is kept but the inlets and outlets are not moved simultaneously at the end of one global period. During a global period (period between two shifts) the time is divided into subintervals in order to accomplish local switching: only one inlet or outlet is moved. Consequently the different inlets or outlets are moved one after the other instead of simultaneously, Fig. 10. As the total number of columns is constant in the process, the number of columns in each SMBR zone (separation, reaction…) changes during each subintervals of the global period but it returns to its initial value at the end of the global period. This non synchronous shifting during a global shifting period increases the flexibility in column distribution compared to the previous process without adding costs. Besides, for the same SMBR performances, it is expected that the implementation of this solution would result in a reduced number of the total number of columns (the current experimental validations lead to withdraw one column in the system with the same performances in terms of purity but with a reduced operating cost). Indeed, thanks to the flexibility created, the number of columns in each zone could change according to the desired requirements for reaction and separation. This can be achieved because both previous operations do not require the same resources at the same time. This solution would enable in decreasing the environmental impact (better use of energy and materials) and the operating costs.

Finally, thanks to the approach presented, a technological innovation is proposed in the field of process intensification by substituting a reactor and a separator by an integrated device. In addition, the changes in the operating procedure resulted in

Table 3
Resources identification.

	Reactor	Separator
Substances	Catalyst (solid), meth (liquid), Ac (liquid) meth Ac (liquid), W (liquid), sulphuric acid (liquid)	Adsorbent (solid), meth (liquid), Ac (liquid), meth Ac (liquid), W (liquid), eluent (liquid)
Fields	Thermal, mechanical (mixing), pressure, chemical	Thermal, chemical (diffusion), mechanical (switching), Pressure…
Time	Filling, reaction time, sewage	Interval between two switches, waiting time before separation (batch process)
Space	Inside the reactor, between reactor and separator	Between columns, void inside the columns
Information	Reaction, thermodynamic equilibrium, athermal reaction	None

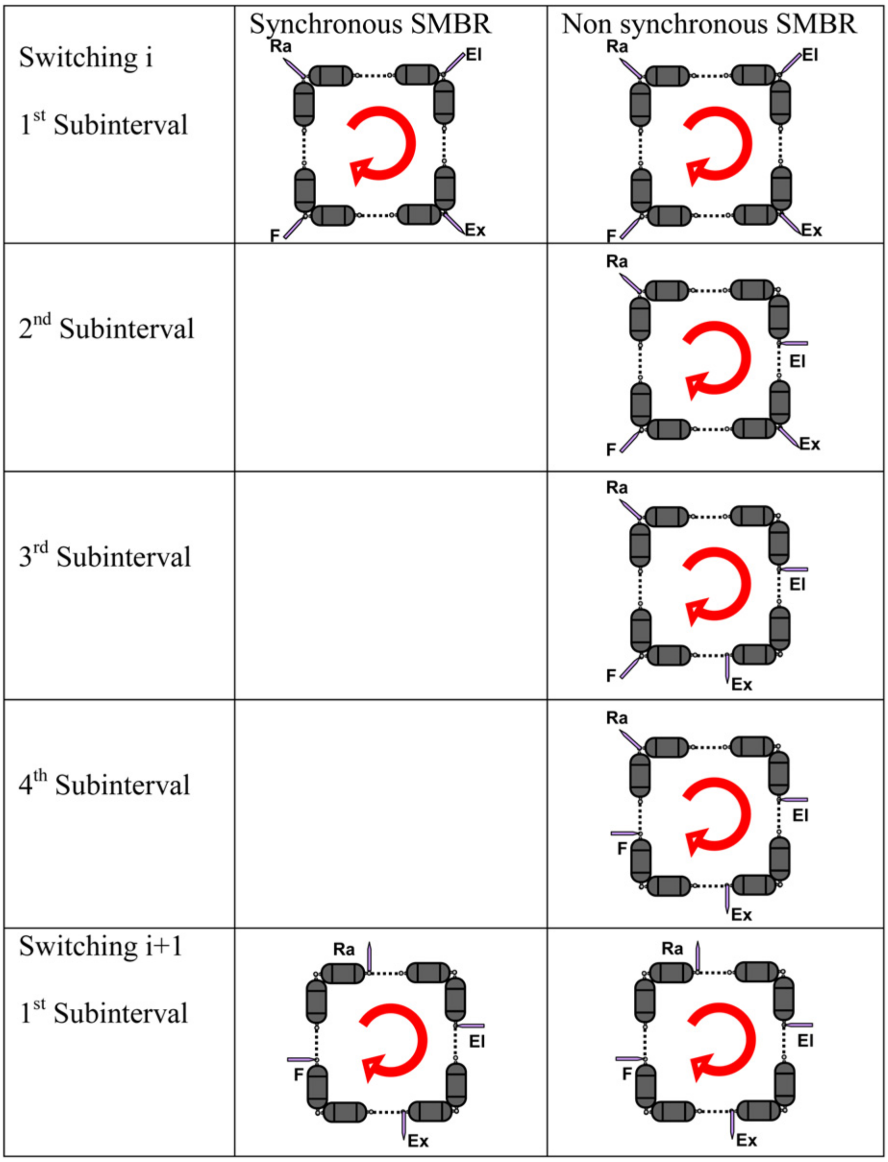

Fig. 10. Procedure for the propose solution.

a complication of the technology but the gains (in terms of environmental impact, operating cost, production efficacy, flexibility) are substantial. Here, the concepts of solution must be improved by simulation and/or experimental studies before proceeding with a detailed design and optimization (of operating conditions) phases. These substantial improvements in process performance should lead to promising applications in fine chemistry and pharmaceutical industry.

5. Conclusion

Unlike most of the eco-design method focus on optimization or minor changes in the design of process, this work proposes an approach to go further in order to deal with the eco-invention issues. The goal is to include as soon as possible the environmental constraints in the invention process. The proposed approach allows to guide the engineers in the solving process in order to systematize the generation of eco-friendly inventive concepts. The proposed approach is an extended version of a previous synergy between (TRIZ) and CBR especially dedicated to eco-invention. This new methodology is based on three major developments:

An extended list of engineering parameters allowing the statement of eco-contradictions. This results in an evolution of the contradiction matrix by including the seven eco-parameters from the WBCSD.

The introduction of all the resources as specific constraints of the problem. This leads to maximizing the use of resources already present in the system, on one hand and a minimization of the insertion of virgin materials in the new solution on the other hand. This is achieved by an adaptability criterion that ranks the solution alternatives with respect to the resources quantity, quality, cost and localization.

The proposition of more concrete solutions than the guidelines of (TRIZ) while maintaining a certain conceptual and utilization simplicity for non-expert. Indeed, after a detailed analysis, the 40 principles were linked with the physical, chemical, geometrical effects or phenomenon. These are proposed as solutions leading to more concrete knowledge. This way to model the problem allows to increase the complexity of the problems addressed by solving models formulated with several contradictions and integrating resources constraints.

This approach offers various research perspectives. Other (TRIZ) method and tools could be integrated in the methodology such as Substance—Field analysis. This analysis is an analogical tool for modelling problems related to existing technological systems. In a system the desired (or none desired, harmful, or insufficient) function is the output from interaction between a substance (S1), caused by another substance (S2) with the help of some types of energy (F). The action is accomplished by the mean of a field. Substance—Field analysis provides a fast and simple model to use for considering different ideas drawn from knowledge base. This analysis is very interesting because it can be used to zoom in the zone of interest. Furthermore, it is connected with basic rules (76 standard solutions) to solve some of the classical problems.

Additional efforts should be done to reduce the subjectivity of the adaptability factors. They are too dependent of the user's perception of the problem and its sensitivity. Although, it is still imperfect it has the merit to provide additional information to support decision.

The last perspective is related to the current developments in the field of Computer Aided Innovation presented by Husig and Kohn (2011). The first one is technological with the possibilities in the software field community with the Web 2.0. The second is more strategic with the open innovation paradigm, as companies start to interact with people outside the company in order to improve their knowledge base and innovative capabilities. The future developments of the tool must integrate both evolutions.

References

Altshuller, G.S., 1996. And Suddenly the Inventor, second ed. MA Technical Innovation Center, Worcester.

Bocken, N.M.P., Allwood, J.M., Willey, A.R., King, J.M.H., 2011. Development of an eco-ideation tool to identify stepwise greenhouse gas emissions reduction options for consumer goods. Journal of Cleaner Production 19, 1279—1287.

Carillo-Hermosilla, J., Del Rio, P., Konnola, T., 2010. Diversity of eco-innovations: reflections from selected case studies. Journal of Cleaner Production 18, 1073—1083.

Cascini, G., Rissone, P., Rotini, F., Russo, D., 2011. Systematic design through the integration of TRIZ and optimization tools. Procedia Engineering 9, 674—679.

Cavallucci, D., Rousselot, F., Renaud, J., 2010. Comparaison de la méthode de conception inventive (MCI) basée sur la TRIZ et de l'approche du raisonnement à partir de cas. In 18ème Atelier de RàPC, Strasbourg, pp. 25—35.

Chang, H.T., Chen, J.L., 2004. The conflict problem solving CAD software integrating TRIZ into eco-innovation. Advances in Engineering Software 33, 553—566.

Chen, J.L., Liu, C.C., 2001. An eco-innovative design approach incorporating the TRIZ method without contradiction analysis. Journal of Sustainable Product Design 1, 63—272.

Cortes Robles, G., Negny, S., Le Lann, J.M., 2004. Knowledge Management and TRIZ: A Model for Knowledge Capitalization and Innovation, Conference. ETRIA, Florence, Italy.

Cortes Robles, G., Negny, S., Le Lann, J.M., 2009. Case based reasoning and TRIZ: a coupling for innovative conception in chemical engineering. Chemical Engineering and Processing 48 (1), 239—249.

Desimone, L.D., Popoff, F., 1997. Eco-efficiency the Business Link to Sustainable Development. Mass. Massachusetts Institute of Technology Press, Cambridge.

Domb, E., 2000. Managing Creativity for Project Success. In: Proceeding of the 7th Project Leadership Conference.

Estevez, I., Dubois, S., Gartiser, N., Renaud, J., Caillaud, E., 2006. Le raisonnement à partir de cas est il utilisable pour l'aide à la conception inventive. In: 14 Atelier de Raisonnement à Partir de Cas Besançon, pp. 123—129.

Finnie, G., Sun, Z., 2003. R5 model for case-based reasoning, knowledge. Based Systems 16, 59—65.

Fresner, J., Jantschgi, J., Birkel, S., Barnthaler, J., Krenn, C., 2010. The theory of inventive problem solving (TRIZ) as option generation tool within cleaner production projects. Journal of Cleaner Production 18, 128—136.

Giudice, F., La Rosa, G., Risitano, A., 2005. Materials selection in the life-cycle design process: a method to integrate mechanical and environmental performances in optimal choice. Materials and Design 26, 9—20.

Grote, C.A., Jones, R.M., Blount, G.N., Goodyer, J., Shayler, M., 2007. An approach to the EuP directive and the application of the economic eco-design for complex products. International Journal of Production Research 45, 4099—4117.

Gupta, S.M., Veerakamolmal, P., 2000. A case-based reasoning approach for optimal planning of multi-Product/Multi-Manufacturer disassembly processes. International Journal of Environmentally Conscious Design and Manufacturing 9 (1), 15—25.

Husig, S., Kohn, S., 2011. "Open CAI 2.0" — Computer aided innovation in the era of open innovation and web 2.0. Computers in Industry 62, 407—413.

Ilgin, M.A., Gupta, S.M., 2010. Environmentally conscious manufacturing and product recovery (ECMPRO): a review of the state of the art. Journal of Environmental Management 91, 563—591.

Jones, E., Stanton, N.A., Harrison, D., 2001. Applying structured methods to eco-innovation. An evaluation of product ideas tree diagram. DesignStudies 22 (6), 519—542.

Kobayashi, H., 2006. A systematic approach to eco-innovative product design based on life cycle planning. Advanced Engineering Informatics 20, 113—125.

Kolodner, J., 1993. Case-Based Reasoning. Morgan Kaufmann Publishers, Inc.

Leon, N., 2009. The future of computer-aided innovation. Computer in Industry 60, 539—550.

Li, T., Huang, H., 2009. Applying TRIZ and fuzzy AHP to develop innovative design for automated manufacturing systems. Expert Systems with Applications 36, 8302—8312.

Livotov, P., 2001. Approach to complete search of innovation concepts and customization of TRIZ tool. ETRIA conference.

Lopez de Mantaras, R., Mc Sherry, D., Bridge, D., Leake, D., Smyth, B., Craw, S., Faltings, B., Lou Maher, M., Cox, M.T., Forbus, K., Keane, M., Aamodt, A., Watson, I., 2006. Retrieval, reuse, revision and retention in case based reasoning. The Knowledge Engineering Review 20 (3), 215—240.

Negny, S., Le Lann, J.M., 2008. Case-based reasoning for chemical engineering design. Chemical Engineering Research and Design 86 (6), 648—658.

OECD, 2009. Eco-Innovation in Industry: Enabling Green Growth.

Pal, S.K., Shiu, S.C.K., 2004. Foundations of Soft Case-Based Reasoning. Wiley Interscience, New Jersey.

Richter, M., Aamodt, A., 2006. Case-Based reasoning foundations. The Knowledge Engineering Review 20 (3), 203—207.

Riesco, H., Negny, S., Le Lann, J.M., 2010. Effective retrieval and new indexing method for case based reasoning: application in chemical process design. Engineering Applications of Artificial Intelligence 23 (6), 880—894.

Sakao, T., 2007. A QFD-centred design methodology for environmentally conscious product design. International Journal of Production Research 45, 4143—4162.

Samet, W., Ledoux, Y., Nadeau, J.P., 2010. Eco Innovation Tool for Mal'in Software, Application on a Waffle Iron (In: IDMME Virtual Concept, Bordeaux).

Santolaria, M., Olivier Sola, J., Gasol, C.M., Morales Pinzon, T., Rieradevall, J., 2011. Eco-design in innovation driven companies: perception, predictions and the main drivers integration. The Sapnish example. Journal of Cleaner Production 19, 1315—1323.

Schank, R., 1982. Dynamic Memory: a Theory of Learning in Computers and People. Cambridge University Press.

Shih, L.H., Chang, Y.S., Lin, Y.T., 2006. Intelligent evaluation approach for electronic product recycling vi case based reasoning. Advanced Engineering Informatics 20 (2), 137—145.

Smyth, B., Kean, M.T., 1998. Adaptation-guided retrieval: questioning the similarity assumption in reasoning. Artificial Intelligence. 102 (2), 249—293.

Srinivasan, R., Kraslawski, A., 2006. Application of the TRIZ creativity enhancement approach to design of inherently safer chemical processes. Chemical Engineering and Processing 45, 507—514.

Tseng, H.E., Chang, C.C., Li, J.D., 2008. Modular design to support green life-cycle engineering. Expert Systems with Applications 34, 2524—2537.

Veerakamolmal, P., Gupta, S.M., 2002. A case based reasoning approach for automating disassembly process planning. Journal of Intelligent Manufacturing 13, 47—60.

Vezzetti, E., Moos, S., Kretli, S., 2011. A product lifecycle management methodology for supporting knowledge reuse in the consumer packaged goods domain. Computer-Aided Design. doi:10.1016/j.cad.2011.06.025.

Wu, M.C., Lo, Y.F., Hsu, S.H., 2008. A fuzzy CBR technique for generating product ideas. Expert Systems with Applications 34, 530—540.

Yang, C.J., Chen, J.L. Submitted for publication. Forecasting the design of eco-products by integrating TRIZ evolution patterns with CBR and Simple LCA methods. Expert Systems with Applications. Doi: 10.1016/j.eswa.2011.08.150.

Yang, C.J., Chen, J.L., 2011. Accelerating preliminary eco-innovation design for products that integrates case-based reasoning and TRIZ method. Journal of Cleaner Production 19, 998—1006.

Zha, X.F., Du, H., 2006. Knowledge-intensive collaborative design modelling and support Part I: review, distributed models and framework. Computers in Industry 57, 39—55.

Zhou, C.C., Yin, G.F., Hu, X.B., 2009. Multi-objective optimization of material selection for sustainable products: artificial neural networks and genetic algorithm approach. Materials and Design 30, 1209—1215.

Glossary

ARIZ: Russian acronym for Algorithm of Inventive Problem Solving
CBR: Case Based Reasoning
OECD: Organisation for Economic Co-operation Development
SMB: Simulated Moving Bed
SMBR: Simulated Moving Bed Reactive
Su—Fi: Substance—Field
TMB: True Moving Bed
TRIZ: Russian acronym for Theory of Inventive Problem Solving
WBCSD: World Business Council of Sustainable Development