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Eco-innovative design method for process engineering

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ABSTRACT

Due to the environmental issues, innovation is one way to challenge eco-friendly technologies, create new process options which are needed to meet the increasing demands for sustainable production. To accelerate and improve eco-innovative design, there is a need for the computer aided eco-innovation tools to support engineers in the preliminary design phase. Currently, several computer aided innovation tools with a clear focus on specific innovation tasks exist but very few of them deal with the eco-innovation issues. Therefore the purpose of this paper is to present the development of a computer aided model based preliminary design methodology focused on technological eco-innovation for chemical engineering. This methodology is based on modified tools of the structured TRIZ theory. The general systematic framework gives the same level of importance, to the technological and environmental requirements during the conceptual design phase. Integrating environment oriented design approach at the earliest, in the design phase, is essential for product effectiveness and future development. The methodology employs a decomposition based solution approach in hierarchical steps by analysing the problem faced, formulation of the problem and the generation of possible and feasible ideas. At each step, various methods and tools will be needed. In this paper some existing tools are adapted to chemical engineering and some tools of the structured TRIZ theory are modified and improved to build a specific methodology oriented towards the increasing technological complexity and environmental issues of current designs.

Undoubtedly, the selection of materials and substances for a particular generated concept, mainly affects the structure, mechanical factors (processability and dimensions) and the environmental impact. In order to deal with these environmental criteria, the resources and their impacts are considered in the upstream phase of the design process and are introduced as constraints in our model.

To highlight its capabilities, the methodology is illustrated through a case study dedicated to tars and ashes issues in biomass gasification.

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1. Introduction

In the current world market evolution and industrial context, the process industries have to face several new trends. For industries this new context enhances the need of increasing product and process innovation for maintaining competitive position or to successfully penetrate into a saturated market. Generally, in chemical engineering few technological innovations have been identified over the past twenty years compared to other engineering domains. But currently, most significant developments are taking place, for instance with the advent of process intensification.

Notaro (2001) notices (for separation technologies but it can be extended to the whole chemical engineering domain), that to meet these new challenges the knowledge base and innovative output need to expand considerably for the development of new concepts and equipments. At the same time, industrial evolutions generate design problems with an increasing level of complexity. These requirements result in a strong need to devise new and efficient methods to accelerate the generation of creative ideas and to systematize the invention for radically new products or processes. Unfortunately, as (Srinivasan & Kraslawski, 2006) underlined, chemical engineering research community shows a weak interest in innovation and creativity compared to other engineering disciplines. Indeed the industrial short term strategies, for instance, a reduced time to market, short return on invests or rapid profits, force the chemical process engineers to continue to develop ideas that are based on existing or similar product or process, i.e. use of intra-domain analogies during design. This way to proceed clearly restricts the generation of new concepts, though provide incremental innovations with continuous and significant improvements but without real technological changes. On the contrary, disruptive innovation tries to generate completely new concepts leading to technological breakthroughs. Thus, capability to facilitate process or product innovations in a new market becomes a crucial advantage. As a result companies must carry both innovation strategies, i.e. incremental and disruptive. With the former they

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Nomenclature

C	finite set of constraints
C_k	constraint k of C
C_{Re}	criterion for resource qualification
C_o^k	cost of resource k
D	finite set of domains
D_i	domain of possible values for variable X_i
E	solution space
EP	environmental parameter
L_o^i	localization estimation of resource k
Nres	number of resources
P_j	space covered by parameter j
Q_l^k	quality qualification for resource k
Q_t^k	quantity qualification of resource k
R_e^k	recyclability of resource k
V	finite set of variables
X_i	Variable i of V

retain their customers and ensure their financial health in the short term. But by too much focusing on incremental innovation, they are exposed to the market arrival of a new competing product or process. Consequently, they must initiate a deeper research program focused on radically new technological solutions with the eventuality that they may render obsolete existing solutions. Some companies are reluctant to take the risks associated with disruptive innovation and prefer to work for the satisfaction of customer requirements only, that undermines sustainability over the long term (Christensen, 2003).

Furthermore, the topic of innovation is of vital interest for chemical companies not only to improve competiveness and increase benefits but also to reshape their product portfolio (Klatt & Marquardt, 2009) and to account for the new challenges of sustainable production. Indeed, for a long time the design phase was widely guided by technological and economical developments which did not lead to products or processes innovations that take into account these environmental concerns. Even if the "environmental image" was a great value for companies both internally and externally, they preferred the novelty and economic criteria of their innovative products rather than a strategy oriented towards sustainable production. In recent years, the expansion of companies' activities has been accompanied by growing environmental concerns: climate change, energy security and resources scarcity. This environmental sensitiveness can give crucial competitive and economic advantage, provided that products or processes satisfying the customers' requirements. Hence, there is a growing trend to voluntarily improve their environmental performances in order to increase profitability, efficiency, and competitiveness but also imposed by legislation like on gas emission. But the incremental progresses are far from meeting the efficiency required by this pressing challenge. Even if the chemical industries have the potential to become a driving force for eco-friendly production, this challenge must be coupled with the economical reality of the current market. Innovation is one possible answer to this issue, provided introducing the environmental constraints in the earliest phase of the design process, and also by increasing their weight in the decision process. In its report, the Organization for Economic Co-operation Development – OECD (2009) describes and details the gradual evolution of the industrial initiatives:

- *Pollution control and treatment*: Technological improvements in order to reduce wastes and contaminants in outlet streams. It does not restructure the existing process but devices are added at the final stages of the process.
- *Cleaner production*: Approach focused on the roots of pollution. The process is modified in order to decrease its environmental impact. Various eco-design tools and approaches are available, resulting in incremental changes on the environmental impact: redesign modification or optimization of existing products or processes; reducing process discharges, decrease of material used, saving energy, efficient resource use, substitution of materials.
- *Life cycling thinking*: New proactive approaches in which the environmental considerations are beyond the boundaries of the production process to the whole value chain. Life cycle assessment is one of the most widely used tools. The concept of green supply chain management has also emerged from this thinking.
- *Closed loop production*: Raw materials that are existing in the system are recycled: remanufactured, mechanical recycling, material recycling, energy valorization, etc. The products or processes are designed with this idea in mind that, they must be reused in one form or another (circular production and economy).
- *Industrial ecology*: The extensive application of the previous production across industries at large scale is called industrial ecology. Eco-parks (cluster of companies that share resources) are an example of this kind of cooperation: a waste for one company can be used as raw materials for another one.

Now a need arises for methods specifically oriented towards the technical innovation that takes into account the environmental issues during the preliminary design phase in order to generate innovative and eco-friendly products or processes, i.e. eco-innovation (Jones & Harrison, 2000) gave the following definition of the eco-innovative: "Eco-innovation aims to develop new products, processes and services that are not based on redesign or incremental changes to the existing product but rather in providing the consumer with the function that they require in the most eco-efficient way." The industry and research communities had developed several approaches to answer to the challenge of eco-innovation for sustainable products or processes, but they are dedicated to estimate the merits of new product (Brezet, 1996; Fussler & James, 1996) or they are directed towards strategy (Cramer & Stevels, 1997). Very few of them are focused on the development and deployment of reliable methods and software to support process engineers generating eco-innovative technical solutions. As Chang (2005) underlined, the designers need faster and systematic methods to develop eco-innovative solutions, especially in the conceptual design phase. The goal of our article is to propose an approach for eco-innovation based on improvements of some TRIZ tools in order to avoid four of its principal drawbacks when dealing with eco-invention, i.e. integration of eco-inventive aspects, evolution to deal with the growing complexity of current design, decreasing the level of abstraction of the proposed solution and the integration of a resources oriented search to ensure a better use of them (Table 1).

The remainder of this article is structured as follow: the second part presents and discusses the existing computer aided innovation tools and the current approaches to deal with eco-innovative design. It also discusses the TRIZ theory used in the proposed approach. The subsequent part presents the workflow of our approach with some explanations on the tools specifically created. The fourth part proposes a case study related to biomass gasification and more precisely to tar and ash withdrawal, to illustrate the main concepts of the methodology. The following part deals with a discussion on the strengths and weaknesses of the methodology. Finally, in part six, a conclusion is drawn and future perspectives are discussed.

Table 1
Parameters to calculate resources qualification criterion.

Q_t^k		Q_1^k		C_0^k		L_0^k		R_e^k	
Missing	0	Waste, harmful, toxic	0.3	Very expensive	0.3	Super system	0.3	Non recyclable	0
Insufficient	0.6	Useless neutral	0.6	Expensive	0.6	Sub systems	0.6	Energy valorization	0.3
Sufficient	1	Useful, easy to recycle	1	Free	1	System	1	Material valorization	0.7
								Functional reuse	1

2. Methods and tools for innovation and eco-innovation

2.1. Computer aided innovation

The innovation process is undoubtedly iterative, collaborative, interactive, multi-tasks and depends on the context. Firms try to improve their innovation capabilities to accomplish this complex and time consuming process from idea generation to successful market diffusion. To reduce significantly the development time, new methods and tools to support innovation activities are created. In the software field, there is an emerging issue to support firms' innovation process not only on the activity of the technological design but throughout the entire process using computer aided innovation tools (CAI). Despite a growing research community, current CAI tools focus on specific aspect of the innovation process (Hüsig & Kohn, 2009) proposed a categorization scheme of CAI, illustrated in Fig. 1. The first category of CAI helps innovation manager to deal with strategic issues with business intelligence tools for example. The Idea Management category starts from idea generation to idea evaluation. The last category focuses on patents because they have a crucial role in the innovation process: to protect firms' inventions and to initiate idea generation. According to Hüsig and Kohn (2009), the potential benefits of CAI tools can be summed up as follows: efficiency, effectiveness, competence, and creativity enhancing. In this paper, we focus our attention to the idea generation and idea collection sub-items. Many software tools exist in this category but we propose to go further in order to include environmental issue at this stage and to improve the processing of current problem complexity. Among the existing tools, different creativity and idea generation techniques (mind mapping, synectics, brainstorming. . .) have been implemented but TRIZ dominates this category as a method for technology forecasting (besides the first software tools that are at the root of the CAI were based on TRIZ).

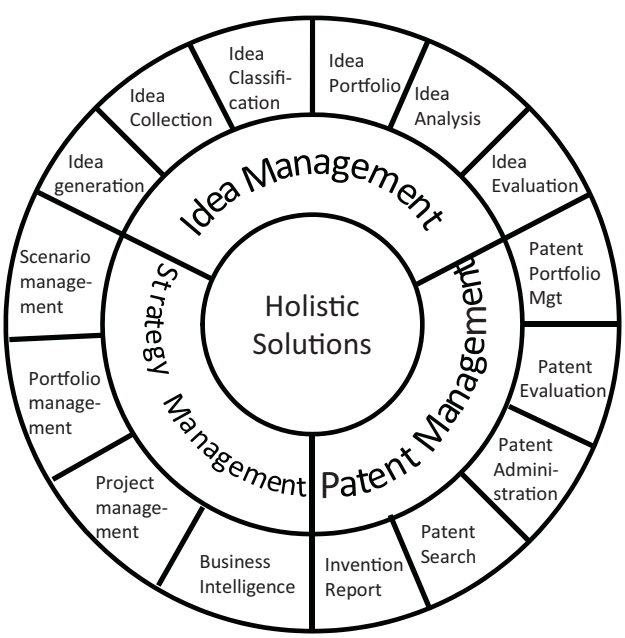


Fig. 1. Detail CAI software categories (Hüsig & Kohn, 2009).

Srinivasan and Kraslawski (2006), Adam, Beniston, and Childs (2009) discuss the creativity issue respectively in chemical engineering and biotechnology domains. Regardless of the engineering domain, to reach highest innovative solutions, we must devise a collaborative working environment that enables domain experts to share their vision of the peculiar problem requirements, to exchange ideas in order to generate unexpected solutions. The generation of very innovative concepts requires cross and trans disciplinary collaboration between experts in different fundamental disciplines. Nevertheless, experts must increasingly have a T shape profile: a wide field of knowledge in order to be an innovator and by definition a sharp knowledge in their field of competence. This contradiction in term of human skills was resolved with trans disciplinary methods that deal with creativity and give access to a huge set of knowledge.

The several specific methods dealing with creativity can be classified into two main categories: analytical or intuitive methods, (Srinivasan & Kraslawski, 2006). The latter searches solutions with a random process because they do not have a formalized logical structure among them; brainstorming, lateral thinking, mind mapping. In these methods the creativity process is composed of two successive logics of actions: divergence then convergence. During the divergent part, engineers generate randomly as many ideas as possible along many directions. The convergent part tries to manage them by merging some solutions or eliminating the less promising ones thanks to a multicriteria decision but with the strong risk to loose very promising concepts. On the contrary analytical methods partially removes the previous issue by proposing well-structured methods like morphological analysis or TRIZ. In TRIZ, the creativity process is solely converging because it postulates that no matter the number of concepts generated quality prevailing, i.e. viability of the concepts.

TRIZ is the Russian acronym for theory of inventive problem solving. TRIZ operates through generic models i.e. patterns of problems and solutions and not by spontaneous creativity of individual groups. To create TRIZ, Altshuller (1996) had conducted scientific observations and a huge analysis of invariants of problem resolution during past innovation and scientific discoveries. He found out that inventive solutions were the result of certain regularities, repeatability, predictability which govern the creative process rather than a process out of human control. He collected and organized information on past inventions and tried to reformulate the problem in order to identify which technical conflict was solved and how it was solved. Then he built methods and tools that are independent of the field of discovery in order to facilitate trans disciplinary knowledge transfer. As a consequence TRIZ operates through the reformulation of a concrete problem into an abstract one. Its methods and tools allow to find a generic solution to this abstract problem. This generic solution should be adapted to the specific initial problem according to the specific conditions and constraints. These inter-domain analogies allow to reach solutions with a higher level of innovation. TRIZ does not guarantee the systematic generation of creative solutions but provides assistance to engineers and designers by focusing their attention on the

most promising ways of solution. It allows to enhance creativity, but there is still the expression of the creativity of individuals to transform the proposed ways of solution into a concrete one. TRIZ encompasses various tools, but for the remainder of this article, we only detail the contradiction matrix. Appendix 1 describes it for a better understanding of the TRIZ processing and of our approach.

2.2. Eco-innovation approaches

Concerning eco innovative design, most of the studies published in the literature explained how useful TRIZ is for design and highlight, how it can be applied efficiently for this research subject. Fresner, Jantschgi, Birkel, Barnthaler, and Krenn (2010) applied it 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 a five steps process based on the technical contradiction of TRIZ that covers a part of the eco-inventive design process, from the problem formulation to the choice of the first design parameters. Some studies had coupled TRIZ with other methods such as FMEA (Yen & Chen, 2005), design for X tools and life cycle analysis (Grote, Jones, Blount, Goodyer, and Shayler, 2007). Various approaches tried to couple TRIZ and quality function deployment (Chen & Liu, 2003; Kobayashi, 2006; Sakeo, 2007). Kobayashi (2006) proposed a four steps method based on the TRIZ contradiction matrix to improve the ratio: product value/environmental impact. Sakeo (2007) presented another approach coupling TRIZ and QFD but by adding life cycle analysis. Cascini, Rissone, Rotini, and Russo (2011) aimed to bridge systematic invention practice with product lifecycle management systems by integrating TRIZ principles within a computer aided design system.

More recently, Yang and Chen (2011) presented an approach based on the coupling between TRIZ, case based reasoning and life cycle analysis. 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). Samet, Ledoux, and Nadeau (2010) conducted a research on another way to integrate the WBSCD axis in the eco-innovation process and they presented an evolution of their design tool to support innovation (based on TRIZ tools) to deal with eco-innovation problems. All these approaches and methods extended TRIZ capabilities with the support of other approaches but none of them tried to modify and adapt its tools to deal with eco design contradictions. Chen and Liu (2001) develop an eco-innovative method based on the inventive principles but without requiring contradiction formulation. Even if they illustrated the capability of their proposed method, there is a lack of a deep initial analysis on the problematic situation leading to uncertainties in the problem formulation.

Furthermore, all these eco-innovative approaches focused on product design and not on process design, and operated at a high level of abstraction (not concrete enough). Indeed, they gave 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.

2.3. Strengths and weaknesses of TRIZ

Despite significant achievements, numerous success stories and real technological breakthroughs in several companies for instance in automotive, aeronautic, electronic industries, TRIZ is still not well established in chemical engineering. However, TRIZ has several capabilities to offer concrete contributions and future perspectives on research in industrial innovation practice. Among these capabilities, all of its structuring, scientific background and technological roots have already been mentioned. In most of the applications in the literature, TRIZ is used in its original and classical form with some chemical engineering examples among them: heat exchanger (Busov, Mann, & Jirman, 1999), food processing equipment (Totobesola-Barbier, Marouzé, & Giroux, 2002), fluidized bed combustion (Lee, Lee, & Oh, 2002), clogging of a multi-drum filter (Carr, 1999), computer aided software (Braunschweig & Irons, 2002). In their general paper, Poppe and Gras (2002) had described how TRIZ can be successfully applied on specific problems of the process industry.

But because of its high abstract level, chemical engineers have experienced some difficulties. They required refining the generic principles and enriching them with specific domain knowledge. Hence, some researchers had adapted the TRIZ matrix into a narrow field of expertise (Li, Rong, & Kraslawski, 2001; Li, Rong, & Kraslawski, 2002; Li, Rong, Kraslawski, & Nyström, 2003; Srinivasan & Kraslawski, 2006). With these attempts the abstract level is lower resulting in more operational tools but at a loss of generality leading to less inventive solutions in another hand. Indeed, as we explain in the previous part, the most innovative solutions arise with reproducible solution archetypes across technical domains and not in a narrow field. Consequently, such matrices do not correspond to the original logic of TRIZ. This high abstract level is the main issue of TRIZ resulting in difficulties in its application, and particularly for the contradiction matrix. Usually, without practice it is very difficult to reach the contradiction and to adapt generic guidelines of the principles into concrete solutions.

Nevertheless the contradiction matrix has a special place among the TRIZ tools, due to its conceptual simplicity. Unfortunately, it is also the source of many disappointments because of unsuccessful attempts. Indeed, for our purpose, nothing was done for including eco-design issues and for dealing with the increasing complexity of current problems. It becomes difficult to reduce the problematic situation to one and only one contradiction. Unfortunately, the current contradiction matrix cannot afford to solve simultaneously all the remaining contradictions, they must be treated sequentially. But in a more satisfactory approach this solving step must be improved for considering them together to propose more coherent and integrated solutions. Furthermore there is a lack of approach for the initial analysis to clearly identify and extract the contradiction, and then to transpose it with the engineering parameters. The user places its hopes (often disappointed) on the robustness of the tool to bring her/him back to the right principles despite an incorrect contradiction. This is the goal of the next section to propose a framework to improve problem analysis, to decrease the level of abstraction, and to deal with eco-innovation and complexity issues.

3. Design methodology for eco-innovative problem

The design of systems is a creative activity starting from requirements, needs and existing knowledge until the definition of a system, industrially feasible, and satisfying the needs. During the design process imprecision decreases monotonically, Giachetti, Young, Roggatz, Eversheim, and Perrone (1997) showed it graphically in Fig. 2. The different steps of the design process require specific knowledge representation methods. The design process starts from abstract models of the system to reach detailed models at the end of the process. This work is focused on the conceptual design steps and has to deal with specific methods to handle the high level of the models and the linguistic variables.

3.1. Workflow of the methodology

The workflow of the proposed eco-innovative methodology decomposes the problem into three principal steps as illustrated in Fig. 3. Each step is subdivided into several sub-steps where the

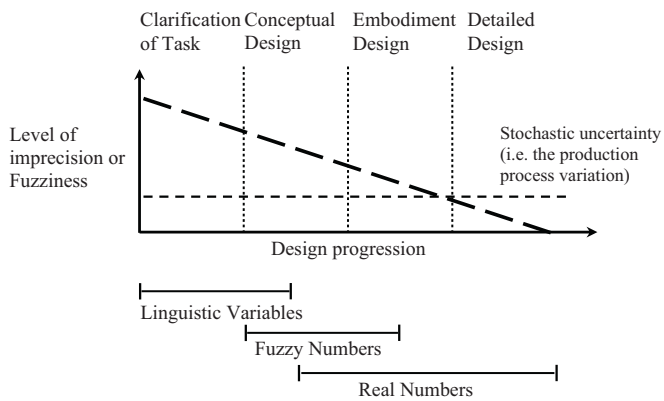


Fig. 2. Design Stages versus imprecision and type of variables (Giachetti et al., 1997).

user adds information on the problem description, constraints or makes some decisions to proceed to the next step or sub-step. To support his actions, existing or specifically created tools and algorithms are used. The workflow containing all the sub-steps and the link between them is detailed in the next sections of this part.

3.2. Problem definition

The goal of this step is to define the technological problem by establishing: the objective of the design, the bottlenecks, and the resources constraints. Thanks to a deep analysis of the problem, the requirements and specifications are reduced to the principal bottlenecks and then the principal contradictions. This first step is broken down into six sub-steps.

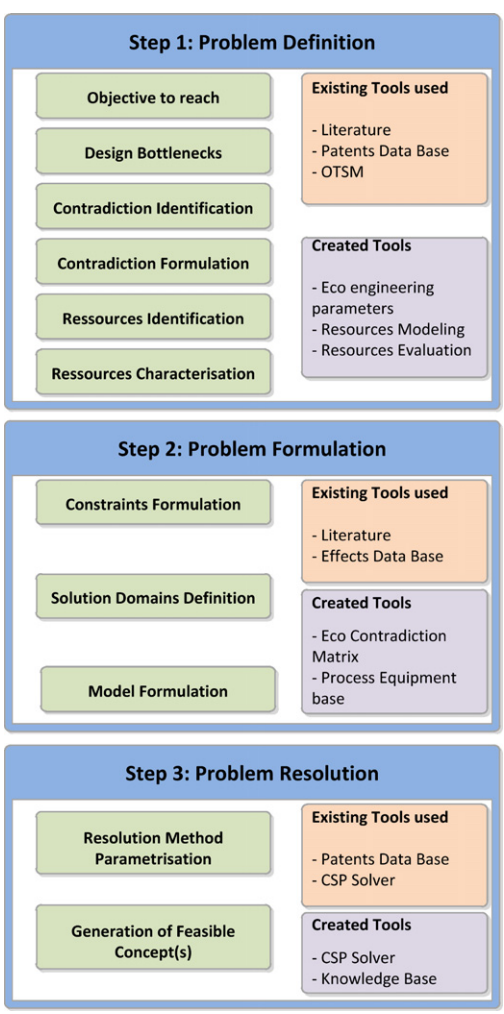


Fig. 3. General workflow of the methodology.

3.2.1. Sub-step 1: Objective to reach

A system is designed in order to realize one (or several) action(s) or function(s). Indeed, it is composed of subsystems which transform or convert inlet fluxes (energy and/or mass) into the desired action. Based on the functional analysis, this vision allows to define the desired function with action verbs: to separate, to disperse, to diffuse, to exchange, etc. In this step, the user selects action verb(s) which represents its design goal to reach. The next steps of the methodology consist of the transformation of the specified functional requirements into design parameters.

3.2.2. Sub-step 2: Define the design bottlenecks

Cavallucci, Khomenko, and Morel (2005) and Khomenko and De Guio (2007) proposed a new formalism of representation to assist designer during the analysis of the problematic situation. This formalism is especially dedicated to innovative design and it is called OTSM method. The first result of their research is a graphical formalization of the problems. This network of problems is a semantic and oriented graph. In a first stage, a list of the most awkward problems is established and a hierarchical ranking is driven according time and space localization of problems. If some partial solutions appear, they are included and linked to their initiatory sub problems. Then the network is built, leading to a clear picture of the whole problematic situation: goal to achieve, sub problems, partial solution and connections between them. The last stage consists of identifying the major bottlenecks in the network with the idea that behind each ones there is a contradiction hidden.

3.2.3. Sub-step 3: Contradictions identification

In this sub-step the previous network of problems is turned into a network of contradictions. Here again, this sub-step is based on a semantic tree of the OTSM method that transforms the bottlenecks into technical contradictions. Then this network is pruned to reduce it to the most challenging contradictions towards which mutual interests converge. Its goal is to decrease the complexity by reducing the number of contradictions. Three reduction modes were identified: center of importance, evolution and resource oriented. We use these previous two networks for our problem formalization because thanks to their strengths and complementarities they allow to manage the complexity on the one hand. They also create a collaborative working environment where experts with different technical skills can easily have interaction, understand problem and propose shared representation of the problems on the other hand.

3.2.4. Sub-step 4: Contradictions formulation

Of course, this phase must be always largely guided by technological and market development. Consequently, the contradiction formulation with the classical TRIZ engineering parameters is preserved. But, as our approach proposes to develop an eco-innovative method, we must enlarge them in order to formulate specific contradictions dedicated to environmental constraints. The World Business Council for Sustainable Development (WBCSD) has developed seven eco-friendly elements that can be used by engineers as eco innovative target for new design. They are used in order to reduce the environmental impact of products or processes: material intensity, energy intensity, dispersion of materials or waves, recyclability, use of renewable resources, durability, and service intensity.

These elements gather the principal categories of impacts coming from materials and energy. The first three clearly expressed a decreased of environmental impact resulting from resources

consumption or rejects. Contrariwise, the last four elements give actions and design guidelines that allow to indirectly avoid negative environmental impact. This macroscopic vision of the environmental aspect gives an exhaustive and global approach of all the impacts to support eco-innovation design. This high level of abstraction makes the eco-friendly elements compatible with TRIZ engineering parameters.

With a further definition the eco-friendly elements are considered as engineering parameters (we called them eco-engineering parameters), with the following definitions:

- *EP1-material intensity*: it refers to the impact of materials or substances but also the choice of them and the wastes generated by the system.
- *EP2-energy intensity*: it refers to the energetic efficiency or consumption.
- *EP3-dispersion of materials or waves*: it refers to dispersion or use of toxic substances but it can be extended to the limitation of substances in a system.
- *EP4-recyclability*: it refers to the recyclability of substances considered in its broader sense: functional reuse, material recycling, mechanical recycling, energetic valorization and so on.
- *EP-5 use of renewable resources*: it refers not only to renewable resources but also to the use of resources available in the system and its vicinity.
- *EP6-durability*: it refers to the lifetime of a system.
- *EP7-service intensity*: it refers to the services associated with the system.

Thus, they are added to the classical engineering parameters to formulate contradictions. We can notice that these seven eco-parameters undoubtedly overlap some initial engineering parameters. EP2 is the most obvious because it is formed through the combination of the engineering parameters; *19 energy spent by a moving object*, *20 energy spent by a none moving object*, *and 22 waste of energy*. Chen and Liu (2001) established the relationships between both types of parameters. Nevertheless, a detailed analysis of the initial parameters reveals that overlaps exist also, but it was decided that it is far more efficient to provide some specific parameters to clearly identify a contradiction. EP2 falls into this 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.

3.2.5. Sub-step 5: Resources identification

Physical, technological and functional aspects of the problem are modelled with contradictions. But in eco design (innovative or not) the resources play a primordial role because of their strong influence on the solution and its environmental impact. Consequently they must be integrated as an important element of the preliminary design stage. The goal of this introduction is not only to optimize the use of resources already present in the system or its vicinity, but also to evaluate in the early steps of design the environmental profile of a product or process to reach more eco-friendly solutions.

Here the term resource is taken in its broadest sense. Obviously it refers to the chemical or materials substances and their associated state, the physical fields (e.g. chemical, mechanical...), time, space but also to additional information on the studied systems. Table in Fig. 4 details the characterization of resources in our approach. The time allows not only to synthesize the time range before, during and after the realization of the various desired function, but also to list the waiting time planned or not. The space refers to void, available or free areas that can be exploited. Chemical reactions are examples of useful information on a system because it can lead to new species (desired or not), new fields (e.g. thermal). This information feature gathers all these important details. The term system specifies the new functions or properties created by modifying the links between sub systems or by new ways to arrange them. The resource localization enlarges the possibility to reach new solutions, and the vision of the problem in order to optimize resources exploitation or to propose more integrated solutions. A resource necessary in one place of the process but is available at another place, leads to question the coupling or the merging between both parts. To ensure the desired functions, resources must interact.

3.2.6. Sub-step 6: Resources characterization

The identification of resources must be accompanied with a characterization useful to improve the performance and the environmental impact factor of the system designed. Consequently, these interactions have to be qualified in terms of quantity, quality. They are also characterized according the following features: toxicity, cost and recyclability. Based on these features, it can be possible to calculate a criterion to evaluate the potentiality of each effect according a resource point of view:

$$C_{Re} = \sum_{k=1}^{\text{Nres}} Q_l^k \times Q_t^k \times C_o^k \times L_o^k \times R_e^k \quad \text{(estimated with Table 1)} \qquad (1)$$

To map and gather all these information on the resources, we built a tool based on the multi-screens analysis of TRIZ, shown in Fig. 4. Each rectangle is composed of a table for resource qualification. Furthermore, its system vision is well appropriated to address the complexity of problems. Indeed, the multi screens view tool considers the interdependence of systems (and also sub systems or super systems) and fluxes between them both in time and space scales. This approach is also interesting in order to ensure coherent and well-structured solutions.

3.3. Problem formulation

The goal of this step is to formulate the problem with a mathematical model. After the problem analysis, all the data and requirements must be traduced as constraints. Furthermore we have to define what will be a solution to a problem. Indeed we could use the TRIZ principles but as previously mentioned in Section 2.3, they are too abstract. Consequently the definition domain of the variables of the model must be specified.

3.3.1. Sub-step 1: Constraints formulation

As explained before TRIZ has a convergent process guided by two categories of constraints: contradictions and specific conditions of the problem. The interest of a convergent design process is to focus on the acquisition of critical data for solving the problem. In addition, reducing the search area, by taking into account the specific conditions, allows the integration of the constraints imposed by the system development and thus to ensure the viability of concepts generated.

Once the problem formalized and pruned to the most important contradictions with the OTSM networks, they are considered as constraints in our model. By considering the contradictions as constraints we limit the research area to the most promising ways by taking advantage of the knowledge gathered in the eco-matrix (presented in sub-step 3).

In our approach, the specific conditions are linked to the research of environmental friendly solution on the one hand and to the goals to reach (function and action) on the other hand. The latter give, the actions or functionalities to achieve by the solution. Consequently, they allow to select the most promising solutions. The former encompasses all the resources available in the system and in its vicinity (the list of resources dawn up with the developed multi-screens tool). In accordance with the most important

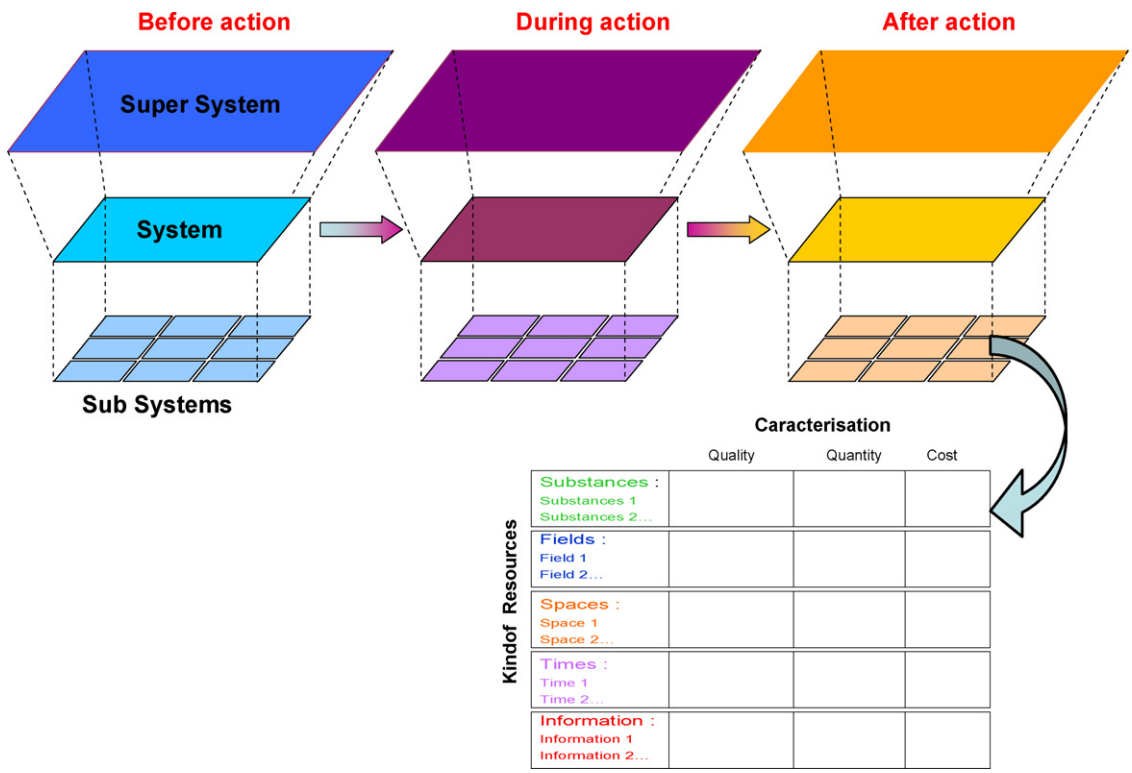


Fig. 4. Enlarged multi screens approach for resource analysis.

pattern of evolution, the system must evolve towards ideality, i.e. maximizing its functionalities and in the same time minimizing the waste and harmful functions. This law advises us to restrict the introduction of new resources. Consequently, the list of available resources reduces the list of possible solutions. For instance, when a conceivable solution needs too much additional resources (fixed by the designer but lower than 3) which are not available in the system or in its vicinity, or when it needs resources with high toxicity or low recyclability, the potential solution is withdrawn from the list. Moreover, some specific constraints on operating parameters can be added, e.g. on pressure, temperature, flow rate etc. After the problem resolution (Step 3), if no solution satisfies all the problem constraints, the designer can interact with the tool to relax some of those constraints.

The model is composed with four classes of constraints:

- *Objective*: action verb.
- *Contradictions*: technical and eco-contradictions.
- *Resources*: characteristics.
- *Specific constraints*: operational, structural, etc.

3.3.2. Sub-step 2: Domains definition

Fig. 5 illustrates the different possible models and the associated knowledge bases offered through TRIZ. Depending on the available knowledge on the problem and the expertise of the designer, TRIZ proposes models with different levels of abstraction. Technical contradictions are situated at the highest level of abstraction, followed by physical contradictions and substances-fields analysis. Next to these models, the solving methods and tools are based on more and more concrete knowledge bases: matrix and the principles for technical contradictions, separation methods for contradictions and finally standards and effects for the substances-fields analysis. On the one hand the contradictions and the resolution matrix provide a tool conceptually simple, easy to use as a first approach. But it remains at a high level of abstraction, resulting in substantial efforts to transcribe and adapt the proposed way of solution into the field of application. On the other hand, substances-fields analysis requires a more detailed analysis of the problem and a more sophisticated understanding of the modelling approach but it is based on more concrete knowledge bases, i.e. standards and effects which are closer to practical solutions. It is interesting to combine the conceptual simplicity of the contradiction matrix with the reality proximity of effects. By this association, we could create a link between these TRIZ tools, nonexistent until now.

Because of the previous reasons, each domain could not be defined with the 40 principles. Besides, to treat the multi contradictions problems (complexity), the number of principles shared by any two contradictions is very small. Worse, the interpretation of each principle depends on the contradiction, the goal to reach and the specific conditions. Consequently, this domain definition seems inappropriate.

At the first time, the level of abstraction of each principle must be decreased. However, the principles do not form a mathematical partition of the solutions space. The principles were detailed but not too refined because a narrow definition should restrict or inhibit creativity. The search for common zones between principles has also a great interest for solving a single contradiction. Indeed, if a common zone exits between some principles gathered in a same cell, it is one preferred direction to explore during the search of a concept. The generated concepts coming from these identified zones often have a higher level of inventiveness because these are the result of a combination of several principles.

After a deep and detailed analysis, each principle was broken down into several clusters; each one consists of translating a search direction into a concrete solution for practice. This is done through the use of physical, biological, chemical or geometrical phenomena or effects which transform the system and its actions. These scientific effects are at the heart of all the transfer phenomena, material conversion, technological accomplishment and technical breakthroughs consequently they form our solution first search domain.

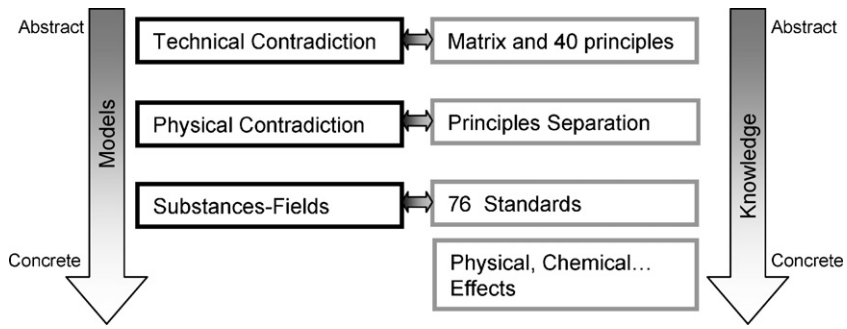


Fig. 5. Model and data knowledge of TRIZ.

Several thousands of effects are registered across all the scientific domains with less than 400 usually applied in industries (moreover in a specific domain an expert knows less than 100 effects). The introduction of new scientific effects or the use of known ones in another context (enlarging its potential applications) leads to propose new inventive ideas. Thus, with our approach, each principle is interpreted according to its original contradiction, and it is attached with a list of possible effects or phenomena that could be applied to solve that specific contradiction.

A database of effects or phenomena was created. This database needs an efficient structure of the knowledge and inference engine to search and store effects from different points of view. As a consequence, the effects and phenomena are not stored by name but the architecture is established from function accomplished and the resources characteristics to implement it.

3.3.3. Sub-step 3: Model formulation

Before to formulate the model, we have to present how we can include the new eco-engineering parameters in the classical TRIZ matrix. Chen and Liu (2001) examined how these seven elements and the 39 engineering parameters of the contradiction matrix are related. Thanks to their relation table, designer can select related engineering parameters under a certain eco-friendly elements. After this selection the matrix is used in its original form. One of the main difficulties of their approach is to find the engineering parameter which is coherent with the eco-friendly element and the design purpose. Furthermore, the links between eco-friendly elements and the engineering parameters are not exhaustive and not always justified. Indeed, they assume that in the initial matrix, the inventive principle which appears often by rows and by columns indicated that their use would lead to a higher success rate. Consequently, association between principles and engineering parameters with a statistical analysis (frequency of association between each principle and each engineering parameter) leads to principles that are never used (e.g. equipotentiality) but they can guide designers towards eco-friendly solutions. The main reason of this drawback is that the frequency of association is not based on an eco-innovative vision. Among the principles "artificially" added in the cells, some have been proved to be inefficient or even irrelevant for solving the contradiction, even if they are statistically relevant to improve the parameter or to avoid the damage of the other one. Besides, the idea of performing their statistical analysis sounds inappropriate because the same inventive principle should be interpreted differently according to the specific contradiction identified.

In our approach, the eco-parameters are added to the classical technical contradiction matrix leading to a 46×46 eco-design matrix, Fig. 6. Next, with the widening of the matrix, new cells are created, and have to be filled with inventive principles. The 40 inventive principles map the whole solution space consequently they are sufficient enough, there is no need to create new ones, confirmed by a new patent analysis (Mann et al., 2003). We have to identify which inventive principle possesses high priority with respect to the new possible contradictions. To ensure the eco innovation vision in the extended matrix, we had analyzed patents dedicated to current eco-innovative designed products, some of them come from the World and European patents data bases, the others from the WBCSD web-site. The data search strategy consists of identifying the eco-design contradiction and then assessing the principles most commonly used for each new contradiction, shown in Fig. 6.

Finally, the model can be summed up as follows:

Constraints:	Solution space:
- Objective	Data base of effects or phenomena (chemical, biological, physical, and geometrical)
- Contradictions	
- Resources	
- Specific constraints	

3.4. Problem resolution

The objective of this step is to identify the best ideas by solving a Constraint Programming problem with respect to all the constraints (operational, technical, structural). Each effect leads to an idea, that once developed will be translated into a promising process option which encompasses a category of process equipment that can be used, modified or improved to establish the effect or phenomena. Subsequently, the final solution needs further design, i.e. detailed design and needs to be validated through experiments.

3.4.1. Sub-step 1: Resolution method parameterization

Once formulated, the problem is solved with a constraint programming (CP) method. Several studies such as Nemati, Steiger, Iyer, and Herschel (2002) have demonstrated that this kind of methods could be used in design-aided tools where the general or expert knowledge can be extracted, explicated and formalized. This

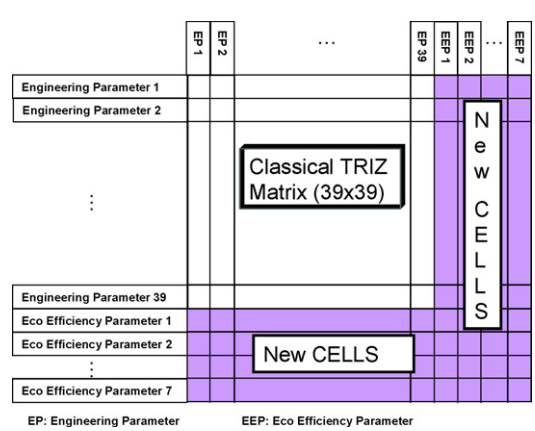


Fig. 6. New eco-contradiction matrix.

implies that the knowledge can be traduced with an element in **C** or several ones in the triplet (**V**: variables, **D**: domains, **C**: constraints).

CP methods are very useful for the conceptual phase of the design process due to:

- Its formalism for attainment, representation and structuration of knowledge which contribute to perpetuate the design activity.
- Its capability to take into account imprecision which is expressed first by linguistic variables then by fuzzy ones (Giachetti et al., 1997).
- Its ability to consider miscellaneous and heterogeneous requirements on the system that allows to consider them simultaneously and thus avoiding iterations along the design process.
- Its possibility to state that a problem has no solution or to find all the possible solutions, i.e. all the design alternatives in our case.
- Its ability to preserve the initial problem structure instead to translate it in another form avoiding loss of information.

These methods (detailed in Appendix 2) combine filtering techniques to reduce the definition domains by using the constraints with tree search algorithm to find solutions. The performances of the method strongly depend on the filtering technique implemented and the order with which the variables and constraints are taken into account. At this last point, some heuristics are integrated into a CP solver: "select first the more constrained variable", "select first the variable with the smallest definition domain", "select first the constraint which encompasses the largest number of variables" etc. Furthermore a CP solver was developed to add functionalities, e.g. choice between several arc consistency algorithms. Before to start the resolution, the user can parameter the methods by choosing some of the previous options (heuristics and arc consistency algorithms). After resolution, if it is stated that the faced problem has no solution, the user goes back to sub-steps 1 or 3 of the 'Problem Formulation' to release some constraints.

3.4.2. Sub-step 2: Generation of feasible concepts

The current inventive problem solving methods require long time to reach solution because each new design starts from scratch. The goal of this sub-step is to propose rapidly an initial feasible solution without restarting the whole creative and design processes. At the end of this sub-step a list of possible chemical process equipment is generated in order to operate the effect found in the preceding sub-step. In order to achieve this, a case base is filled with previous equipment obtained from past solutions found with the methodology or patented solutions (analysis of some patents to fill the base). Then a case based reasoning (CBR) system was created to retrieve a list of candidate unit operations which could involve the proposed effect or phenomena.

The CBR is used to structure the information and the knowledge gathered in the case base but also thanks to its ability to exploit in an efficient and flexible way the knowledge developed during past designs. CBR is a five steps method to exploit, maintain and update a knowledge base. After the presentation of the faced problem (1st Step), the CBR system retrieves (2nd Step) the most similar problem in the case base and tries to reuse (3rd Step) and revise (4th Step) its solution to propose a solution to the initial problem. Once solved, the new problem and its solution can be stored (5th Step) in order to enlarge the case base. The CBR brings several more complex subprocesses explained in Pal and Shiu (2004) with further details for chemical engineering design given in Negny and Le Lann (2008).

In the CBR system of the methodology, to describe the problem faced the user needs: the effect or phenomena to operate or enhance, data on the resources needed (description of streams, state, characteristics, etc.), data on energy (heat exchange, heat generated, energy lower or upper bounds (if necessary)). As a solution the CBR system gives not only a list of process equipment but also for each ones advises and information in the way to successfully implement the effect or phenomena in the unit operation and on the limitations or bottlenecks to avoid.

4. Biomass gasification case study

4.1. Problem statement

With the recent price fluctuations and dwindling fossil fuels resources, there has been a trend towards use of alternative energy sources. Nowadays, biomass is the energy source with the highest potential in response to the requirements in strategies to reduce greenhouse gas emissions. The synthesis gas (syngas) produced by biomass transformations can be used in several applications such as second generation biofuels (methanol, dimethylether, and Fisher-Tropsch diesel) (Van Rossu, Potic, Kersten, & Van Swaaij, 2009), renewable hydrogen production (Florin & Harris, 2007), fuel cells (Xuan, Leung, Leung, & Ni, 2009), cogeneration: heat and electricity.

Biomass solid fuels can be converted into energy via various biological and thermo chemical processes. Depending on the application of the syngas, several thermo chemical conversion methods are available: combustion, pyrolysis, and gasification. Biomass gasification gathers several endothermic reactions between carbon and reacting gas resulting in production of several gases such as: carbon monoxide, hydrogen and traces of methane. Fig. 7 shows schematically the distinct mechanisms that take place in the process.

There are two main types of gasifier technologies; fixed beds classified according to the way air or oxygen are introduced and fluidized beds depending on the gas superficial velocity. The choice from one technology to another depends on many parameters such as the range of expected power, the final use of the syngas, the biomass properties. Fluidized bed reactors are considered to be the most advanced technology with several reactor configurations proposed in the literature. From the industrial point of view the circulating fluidized bed is the more established with processes in Austria, Sweden and Finland, consequently we are interested to improve this technology.

The two major constraints to the biomass gasification development are the diversity of biomass and the presence of pollutants in the syngas. The former gives different properties to the biomass resulting in a strong influence on the operating conditions and on the composition of the pollutants in the syngas. For the latter, after the pyrolysis stage, hydrocarbon compounds, namely tars are created and are harmful to the future use of the syngas: fouling, problems of maintenance. The tars content is directly linked to the quality of biomass and the gasification process retained. Indeed, through their design some processes decrease the presence of these tars, it is particularly the case for the circulating fluidized bed. Unfortunately, they are not completely removed, thus their elimination requires important investment and maintenance costs. With tars, ashes are also generated by inorganics involved. So, they cannot be reduced except by improving biomass quality to have lower ash biomass.

The circulating fluidized bed is schematized on the right part of Fig. 7. Among its strengths we can underline its: good temperature and kinetics control, high flexibility towards fuel (type and size), moderate tars content and high conversion rate. On the other side, it has also some weaknesses like its high concentration of particles, its pressure drop because of ashes and it difficulty to operate with biomass having a percentage of moisture greater than 20%.

4.2. Application of the method

The detailed results of each step of the previous workflow are given with supplementary precisions on the tools used.

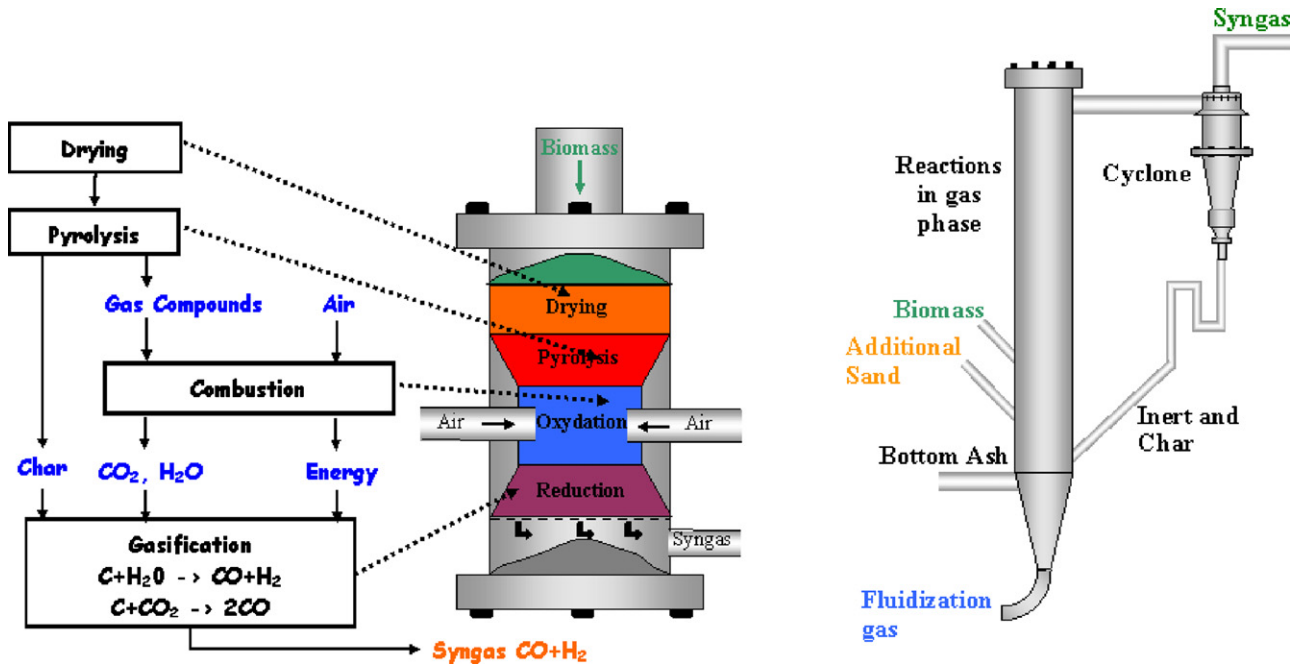


Fig. 7. Mechanisms involved in the gasifier and circulating fluidized bed.

4.2.1. Step 1: Problem definition

Sub-step 1: The minimization of the tars and ashes in the outlet stream of the circulating fluidized bed is used as our goal. Consequently the action verb "To eliminate" is selected. Another purpose of the design is "To increase energy efficiency"

Sub-step 2: In Fig. 8, a small part of the OTSM network of problems is shown for the improvement of biomass power plant. The pollutants generate two major categories of problem; process plant efficiency on the one side and regular maintenance and cleaning on the other side. In theses conditions, it is necessary to reduce their presence or to remove them before the use of the syngas because they generate important operating and maintenance costs. This economic obstacle is the major bottleneck to the expansion of biomass as energy source. Two possible ways of solution could be used: to produce clean syngas at the outlet stream of the gasification chamber or to clean it after production and before use. Another possible solution for regular maintenance could be to stop the process periodically to make the cleaning operations, but with economical consequences and control issues regarding the start up phases. This way of solution is unforeseen because it is out of the scope of our study. Khomenko, De Guio, Lelait, and Kaikov (2007) present another vision of the network of problem for the biomass issue, e.g. they analyzed deeply the previous partial solution "periodically cleaning". Obviously there are similar problems and solutions between both presentations but each one has its own specificity, for instance a more general point of view is given in Khomenko, De Guio, Lelait, and Kaikov (2007) and more chemical engineering oriented vision by us.

In Fig. 8, the sub network arising from the partial solution "Produce Clean Syngas", we can underline that currently, it is difficult to explain the root causes of tars formation. Indeed there is still a poor scientific knowledge concerning their formation mechanisms. This complicates the design of a process in order to try to limit their formations. In this context, we focus on the cleaning branch of the network. The problematic situation can be decomposed into two sub problems: the reduction of tars and ashes. Ashes are carried out by the gas stream of the fluidized bed; therefore another technological apparatus could be imagined to avoid gas flow. This partial solution has a direct impact on the heat recovery between combustion and gasification chambers.

Sub-step 3: The network of contradictions is composed of various types of parameters and relations between them, as shown in table in Fig. 9. The contradictions are represented by symbols as illustrated in Fig. 9; the two outlet arrows express the opposition between two parameters. To prune the macro network into the most challenging contradictions, Cavallucci et al. (2005) had established some rules to use in order to restrict the set of contradictions to the key ones, problems towards which converge mutual interests.

Concerning the tars, the main way of purification is carried out at high temperature between 950 °C and 1100 °C. Unfortunately, the output gasification temperature is around 850 °C. This temperature has an upper limit due to the balance between the temperature of the combustion part, the endothermic reaction, and with the thermal losses. One possible solution to increase temperature in the gasification chamber is to enhance the temperature in the combustion one. But the latter (approximately 1000 °C) is constrained on the one hand by the melting point of ashes and on the other hand by the cash return of the process. Indeed, increasing the temperature means a greater consumption of biomass in this operation and as a result a lower production of syngas. Another available solution was to increase heat exchange between both previous chambers by increasing the gas residence time in the combustion chamber. As a consequence it should be necessary to enhance the size of the combustion chamber and thus the thermal losses. Moreover, the more the residence time is increased, the more the energy flux towards the gasification chamber is reduced.

Another feasible branch of solution for the pollution of syngas is to clean it before use. In these conditions, the syngas also requires a process of purification for removing solid particles of ashes stripped in the output flow and for eliminating tars. Currently, to minimize ashes and tars, the syngas undergoes a succession of two types of complex treatments: furnace, scrubber and heat exchangers for tars and filtering for ashes. Unfortunately, the presence of tars and ashes causes plugs that foul the ducts, requiring regular cleaning, and deposition of tars in the turbines when the syngas

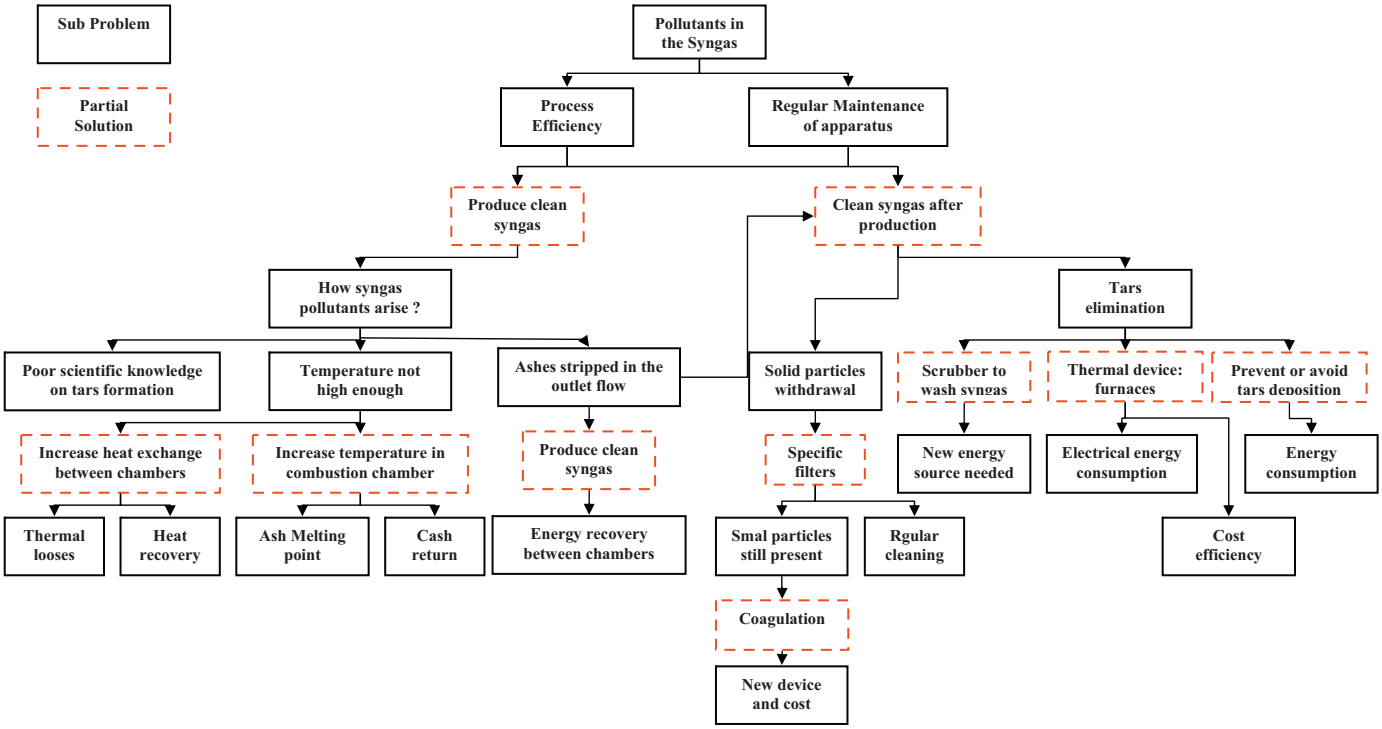


Fig. 8. Network of problems.

is used for cogeneration (engine breakage). It is therefore essential to reduce the costs of cleaning equipment, or even to remove one (or more) step(s) of gas post treatment. In the syngas output stream to deal with the problem of tars specific filters or a coagulation device can be added to the process. Both solutions lead to additional prohibitive costs. Khomenko et al. (2007) had studied more deeply the filter branch but with cost considerations it can be quickly dropped out. Finally, Fig. 9 illustrates the two remaining contradictions concerning the cleaning issues of the syngas leaving the combustion chambers. Each contradiction refers to one of the pollutants to eliminate.

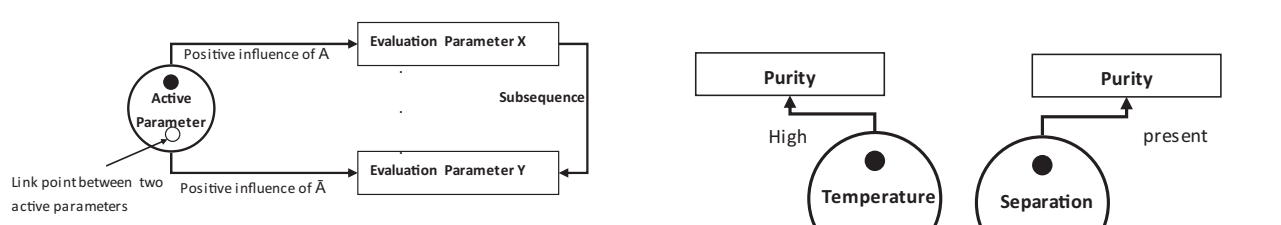
Sub-step 4: The previous contradictions represent the concrete problem. In this step the problem is reformulated at a higher level of abstraction with the parameters of the eco-matrix.

4.2.1.1. Tars. The energy necessary to reduce the tars can be brought through a heat recovery from the combustion part, thus avoiding additional and expensive equipment. In order to be effective, this solution requires a rise in temperature by combustion of a larger fraction of biomass and therefore a loss of production of syngas. The contradiction of this problem can be expressed as follow: the elimination of a substance decreases the productivity. Using the 46 parameters it is modelled by:

amount of substance (26) vs. productivity (39)

4.2.1.2. Ash. The elimination of the solid particles requires additional equipment (specific filter for example) which complicates the process. For this problem, the contradiction is formalized using the following parameters:dispersion of materials or waves (EP3) vs. complexity (36)

Sub-step 5: The resources used in the process are listed thanks to the tool presented in Fig. 3. All the resources are considered, all the chemical compounds and their states, e.g. solid olivine (used to recovery between chambers), air, moisture, but also heat fields, mechanical fields, pressure field, information on reaction, void



Active Parameter	Parameter whose values can change but controlled by designer
Evaluation Parameter	Parameter influenced by changes of Active parameter(s)
Influence	Influence of a parameter
Value A (and opposite Ā)	Limit values of a parameter
Parameters contradiction	Relationship between an active parameter and the two evaluations parameters influenced by its opposite values
Sub sequence	Influence between two evaluations parameters

Fig. 9. Contradictions formulation (Cavallucci et al., 2005), application to biomass gasification.

space inside the chambers, etc. We limit the resources analysis to the system and sub-systems. We do not voluntarily give the exhaustive list of the resource because it is too long and not fundamental for the remainder of the article.

Sub-step 6: Once the list of resources established, they are qualified thanks to formula (1) and Table 1. For the same reasons as the previous sub-steps, this one is not detailed.

4.2.2. Step 2: Problem formulation

The three sub-steps of step 2 lead to problem formulation. Sub-steps 2 and 3 are not detailed in this example because they put in highlight the tools to model a problem and prepare the resolution step: effects data base and new eco-matrix with its new cells. For the biomass gasification case study the model can be sum up with the following constraints:

Objectives:	"To eliminate"
	"To increase energy efficiency"
Contradictions:	Amount of substance vs. productivity
	Dispersion of materials or waves vs. complexity
Resources:	Partial description given in Sub-step 5
Specific constraints:	Temperature in the combustion chamber <1000 °C
	Decrease the size of the devices (compared to current design)
	Decrease the biomass consumption in the combustion chamber

4.2.3. Step 3: Problem resolution

Sub-step 1: The discrete constraint satisfaction Problem was solved with the common AC3 algorithm coupled with the heuristic "Select first variables with the smallest definition domain". Then the remaining available effects are ranked according to the resource criteria.

The geometrical effect "Put a system inside another" and the physical one "Gravitation" are the two principal effects proposed by the model. The first effect leads to the idea to put a device inside the combustion chamber in order to beneficiate of its high temperature and its void space.

In an ideal configuration, the combustion chamber must be directly in contact with the gasification chamber to improve the exchanges by thermal conduction and thus decreasing the temperature difference between both chambers.

To go further with the geometrical effect, the combustion chamber could be placed inside the gasification chamber to increase the exchange surface and thus the thermal transfer. In turn, the gasification chamber could be situated within the storage enclosure in order to not isolate it from the outside in one hand and to dry the biomass before gasification. Indeed the heat from the gasification could also be used to remove water from biomass. However the temperature in the storage tank does not be greater than 150 °C to avoid risk of ignition of the biomass. With the high temperature of the gasification chamber compared to the desired temperature for storage an insulation layer should be interposed between both. This solution with successive overlapping similar as nested dolls will increase the energetic performance of the process. For the circulating fluidized bed, with this solution the limitation due to the percentage of biomass moisture is avoided, this device could be used with biomass with a threshold higher than 20% as it is dried.

Sub-step 2: After the retrieve step, the case based reasoning system proposes several devices with this recommended order of use: heat exchanger, bubble reactor, coagulation device, etc. The first two are more specific to eliminate tars, the latter to withdraw ashes. Based on a combination of the previous equipment a new one was proposed to satisfy the two major requirements and to beneficiate of the controlled temperature in the circulating fluidized bed. In these conditions a new intensified heat exchanger was developed for tars cracking as the level of temperature is high enough to break heavy hydrocarbon into lighter ones by application of heat and pressure (thermal cracking) with the potential use of a catalyst. Catalytic cracking allows to operate under much less severe conditions. As explained before, the major difficulty is that cracking must be carried out at high temperature. But during the resources drawing up, a thermal field that enables to reach the required temperature has been identified in the combustion chamber.

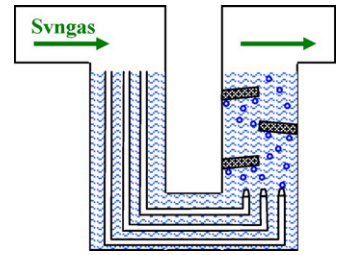


Fig. 10. New intensified heat exchanger.

Fig. 10 gives a mere schematic representation of the patented solution (EP1840191A1, 2007). The device set-up consists of flowing the syngas through a siphon filled with liquid. In the inlet part, the syngas flows inside a bundle of small channels in order to increase its temperature to reach 950 °C, and then it is injected into the liquid in the form of bubbles. The liquid should remain at high temperature but also to have a catalytic effect with respect to the reaction of cracking, if possible. For example molten metals or molten salts with a melting point lower than 900 °C can be used: sodium, sodium hydroxide, potassium hydroxide, lithium carbonate, sodium carbonate, etc. Deflectors are arranged in the bottom part in order to increase the residence time of bubbles in the right of Fig. 10 and consequently the contact time because bubble rise too quickly in the ascending part. This gas–liquid contact also caused the suspension of ashes in the liquid thanks to lift forces. With the gravitational effect ashes can be cleaned by a simple and not very expensive scraper. Another great interest of this solution is that the two pollutants are eliminated in the same device. The effectiveness of this system is enhanced by improving the heat transfer by increasing the exchange surface thanks to mechanical devices: extending the length of multiple channels, adding fins between the compartment containing the liquid and the surroundings environment.

5. Discussion about methodology

The initial version of the methodology has two major limitations: the method and tools to analyze and solve the problem, and the lack of criteria to drive the decision for choosing between alternatives.

First, the following stand-alone methods and tools are discussed multi contradictions resolution, effect database and CBR system on equipments. The evolution of classical TRIZ methods for the resolution of problem expressed with several simultaneous contradictions is one of the principal strength of our method. But after some tests, the method cannot solve problems formulated with more than five simultaneous contradictions. Consequently, the analysis step with OTSM is still very important because it allows to keep the principal sub-problems. But with the increasing complexity of current problems this limitation could reduce the performances of the presented framework. Nevertheless, it permits to manage complexity of process alternatives.

Moreover, technical contradiction remains difficult to identify and formulate because there is fuzziness during the transition from concrete contradiction to the contradiction formulated with engineering parameters (Mann, Dewulf, & Zlotin, 2003). The ideal solution is that users of any technical skills will describe the problem in their own language and ontology. Then, a semantic tool

will analyze the problem description and provide the most suitable inventive principle.

Another idea is that the process improvements can be obtained at the phenomena level. Thanks to the methodology and the effect database, the key phenomena or effects for eliminating the process bottlenecks and enhancing the process performance can be identified. The current database must be enlarged because it gathers effects or phenomena in the domain or the neighboring domain of the chemical engineering. But to support inventions with higher level of inventiveness, the knowledge base of effects or mechanisms must include new ones coming from other technical domain. Indeed we must address to new way to raise bottlenecks of the chemical engineering design issues as on micro-unit operation for example.

In step 3, the CBR is based on past designs. On the one hand it accelerates the design process but on the other hand it limits the creativity. Indeed, it guides the thinking towards existing equipment, but to synthesize new devices the user must overcome the inertia. For example in the case study, the solution combines several device options to develop feasible technical equipment. Consequently, the proposed equipment must be considered as a starting point to generate new ideas and not as an initial solution. This sub-step demands an important abstraction effort to be creative.

The second great limitation concerns the choice to select between solution options. A multiobjective decision support system must be created. Obviously an economic criterion must be coupled with sustainability criteria. These criteria will be important in several sub-steps of the methodology to progressively reduce the search space and to compare with different options. We must address the sustainability criteria with respect to the aim of the methodology. In the conceptual design phase life cycle assessment cannot be used because too many uncertainties remain. Indeed, LCA is very sensitive to minor change in design, e.g. a new species even in small quantity can result in an important on the metrics. For this reason, we aim to develop some specific criteria based on the LCA ones and the sustainability metrics proposed by Institution of Chemical Engineers.

6. Conclusion

Computer aided eco-innovation (CAEI) is an emerging field in the scope of computer aided tools. The goals of CAEI is to support firms during the whole eco-innovation process from perceiving and anticipating market opportunities and demands, to the help to engineers for transforming their eco-invention into eco-innovation. In this process there is a stage for supporting designers for developing more rapidly eco-inventions. This paper presents a computer-aided tool focused on this last stage of a CAEI.

It has been shown that eco-innovation can help to improve existing processes and is needed to lead to sustainable production in chemical engineering industries. A systematic methodology is developed that provides a framework to find feasible process options based on; a deep analysis of the problem faced, a careful collection and analyze of available data in the preliminary design phase, and on effects knowledge bases and process equipment. The stepwise approach determines and integrates the different constraints on a process design: objectives, resources, technological. The methodology needs a number of methods and tools at different sub-steps. Some of these come directly from the literature but most of these were specially created for the purpose of the methodology. Indeed, current methods dealing with eco-innovation or innovation work at a high level of abstraction, often too far from the level required for the implementation of concrete solution. The important tools of the methodology are the eco innovation contradiction matrix (based on the contradiction matrix of the classical TRIZ theory), an effects or phenomena databases to propose feasible and concrete solutions, and a case based reasoning system to exploit a knowledge base gathering process equipment. The methodology has been successfully applied to a case study improving the cleaning of pollutants in the syngas outlet stream of the circulating fluidized bed for biomass gasification.

In part five, the paper has pointed out some issues of the current methodology that can be addressed in future works in order to improve the existing methods and tools but also the whole methodology. Another perspective will be to include modules for anticipating and requiring market opportunities and requirement, for transforming eco-invention into eco-innovation but also for capitalizing and managing the knowledge deployed during design in order to accelerate the innovative design process in order to build a complete CAEI.

Appendix 1. Classical TRIZ contradiction matrix

After its large patent studies, Altshuller (1996) listed some specific recommendations in order to overcome contradictions. He selected the most often occurring strong solutions and finally had extracted 40 universal principles to eradicate them. Each principle is a generic suggestion, a guideline which recommends a certain method for solving inventively a particular problem. It is important to underline that the proposed principles do not give concrete solutions but they limit the research domain by giving a direction to explore before letting the expression of the designer creativity.

The contradiction matrix is a TRIZ tool that maps the most promising principles to use, i.e. link between technical contradiction and the 40 inventive principles identified by their label number, Fig. A1. First the designer matches the meaning of its contradiction with two appropriated parameters. During the patent analysis, Altshuller (1996) identified 39 most common engineering parameters encountered in technical systems that generate technical contradictions. Technical engineering parameters are things that engineers and scientists have to take into consideration when they are designing a solution; weight, length, speed, power, etc. Any contradiction is formalized by a pair of contradictory engineering parameters; the first parameter for the improved feature and the other one for the damaged feature. For example "Length of a stationary object' vs. "Loss of substance' (Fig. A1). To use the contradiction matrix, you have to select the parameter to be improved in the first column and the worsening one in the top row. The numbers in the crossing cell refer to the 3 or 4 most suitable inventive principles ranked in the recommended order of use (statistical result of the patent analysis). These principles were successfully used by other designers to eliminate that specific contradiction. Through the contradiction matrix, TRIZ opens up the world patents bases for identifying principles that may lead to possible solutions. We can sum up the elimination of a technical contradiction with a five steps method (Fig. A1):

Step 1: Translate the problem in the contradiction between two parameters.
Step 2: Identify both parameters among the 39.
Step 3: Use the matrix.
Step 4: Identify the principle to use.
Step 5: Traduce the principle in an operational solution (expression of the creativity).

Appendix 2. Constraint programming

Constraint programming (CP) is a set of problem solving methods based on a declarative description of a problem as a set of decision variables with their domains, and a set of constraints

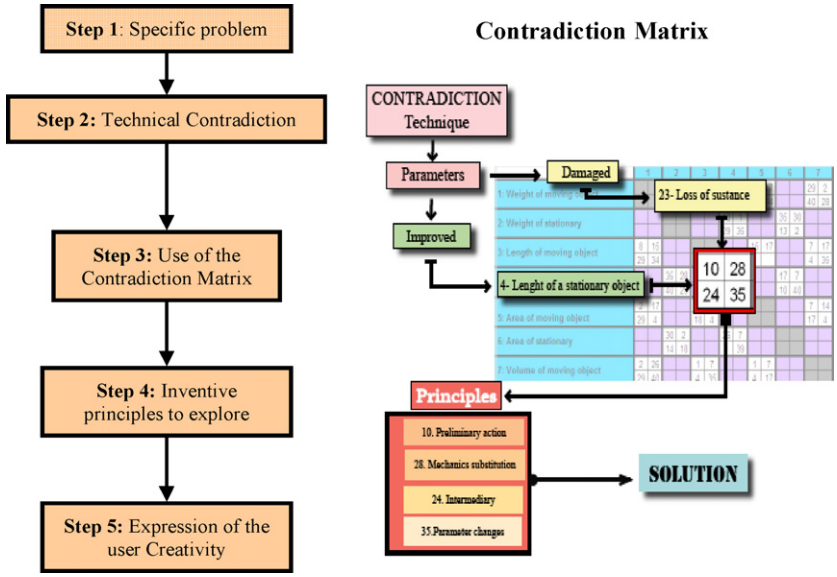


Fig. A1. Five steps method to eradicate a contradiction.

restricting the combinations of values. It is defined by a triplet (**V**, **D**, **C**) with:

- **V** a finite set of variables $\mathbf{V} = (X_1, \ldots, X_n)$.
- **D** a finite set of domains of validity $\mathbf{D} = (D_1, \ldots, D_n)$. Each variable X_i of **V** has an associated domain D_i in **D**.
- **C** the network of constraints $\mathbf{C} = (C_1, \ldots, C_m)$. Each constraint C_j describes the combinations of variables values to authorize or to rule out. The type of constraints determines the classes of the CP and therefore the solving strategies. In the scope of our study, the problems faced are restricted to discrete constraints (besides, in design problems the discrete domains are generally finite).

The question to be answered for this method is whether there exists an assignment of values to variables such that all the constraints are satisfied. Compared to optimization techniques, CP is characterized by a reduction of domains of the variables during resolution. They are used to make deductions on the problem by detecting partial assignments that are locally or totally inconsistent (variables assignments that lead to constraint violation). The key idea is to use *actively* constraints to reduce the computational effort needed to solve high combinatory problems. Constraints are not only used to test the validity of an assignment but also in an active mode to remove values from domains and detect inconsistencies. This process is called constraint propagation or filtering. To accelerate the problem resolution, it is mandatory to obtain a tradeoff between filtering time and its effectiveness. Indeed, several filtering techniques are available, capable to remove more or less values in a more or less important computing time (Lhomme, 1993): node consistency, arc consistency, k consistency. Local consistency consists in verifying that the variables do not violate constraints in which they are encompassed. Arc consistency, used in our approach, offers a good tradeoff between computational effort and filtering effectiveness. Arc consistency verifies that all the values in a variable domain D_i is compatible with each constraint considered separately. Gradually, all the domains can be reduced and when we cannot deduce any domain reduction the filtering steps is finished.

Generally, constraint propagation is usually incomplete. In particular, it cannot detect all the inconsistencies because the constraints are considered separately. Consequently, constraint propagation must be coupled with search techniques to determine if a problem has one, several or no solution. The search is commonly performed with a tree search algorithm. The goal of the search is to go through the tree till a solution is found while the filtering consists of pruning this tree by eliminating local inconstancies. The tree search algorithm can be decomposed into two main parts: the sequence of decision variables (i.e. the way to explore forward the tree) and the definition of the backtracking strategy. The latter explains how the algorithm shall behave when an inconstancy is detected. The most commonly backtracking algorithm (used here) is depth first chronological backtracking but more complex algorithm can be performed. Forward consistency checks combine backtracking with nodes consistency while look ahead checks use arc consistency. The mathematical aspect of CP is more complicated (important research community in this domain), for instance, the resolution strongly depends on the type of variables: discrete or continuous. All these aspects are out of the scope of this paper, but more details can be found in Apt (2003).

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