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TRIZ and MACBETH in Chemical Process Engineering

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Abstract

The Chemical Process Industry (CPI) is facing an increasing pressure to develop new or improved chemical processes. The major challenges experienced by CPI is related with sustainability namely economic, social, and environmental issues, is the reason why innovation in chemical process design is becoming more challenging. However innovative chemical process design needs the support of a systematic innovation approach to guide engineers in the creation of new or improved chemical processes. The objective of this work is to present an approach that integrates the theory of inventive problem solving (TRIZ) and a multicriteria decision analysis method MACBETH for the selection of an improved chemical design among different options. The objective is to establish a systematic innovation approach to assist engineers or decision makers through the idea generation with TRIZ theory, and use MACBETH to perform the selection of the best-generated concept. The use of a combined approach in chemical process improvement may increase the efficiency of concept selection avoiding time waste. An illustration is presented in order to show the simplicity and applicability of the approach.

Keywords: Chemical process engineering, Creativity, Innovative process, M-MACBETH, Theory of inventive problem-solving (TRIZ).

1. Introduction

Sustainability has become a key agenda for chemical process industry (CPI) in face of the increasing environmental challenges, growing awareness of social responsibility and shortages of natural resources (Bonini and Görner, 2011). The chemical process industry (CPI) involves the extraction of raw materials such as crude oil, gas and minerals, processes which are highly energy intensive, and handling of large volume of toxic, flammable, and hazardous chemicals involving different sectors (e.g. oil/petro-chemicals, bulk/specialty chemicals, pharmaceuticals, and consumer products). The study of sustainability trends in process industries performed by Liew et al. (2014) revealed that the top sustainability issues of chemical process industries are very similar and related to health and safety, human rights, reducing GHG, conserving energy/energy efficiency, and community investment. Innovation in chemical product and process design needs to respond effectively to society's challenges by providing solutions for future generations the reason why innovative chemical process design requires the introduction of new methods and tools for generation of technological and organizational solutions. Some of the methods usually applied for creativity enhancement used in chemical industries are brainstorming, brainwriting, lateral thinking, morphological analysis, etc. These methods usually have the ability of identifying or uncovering the problem and its root cause, but lacks the capability to solve those problems because they do not point clearly to ways of solving problems, or highlight the right solutions (Savransky, 2001). The use of a systematic process for invention, with a logical formal structure covering the different aspects of the systems, will accelerate the problem solving in a creative way and give the confidence that a wide range of possibilities of new solutions have been covered, breaking up the psychological inertia to innovation and inventive problem solving (Gadd, 2011). A systematic process for invention leads to problem solving methods based on logic and data, not intuition, which accelerates the project team's ability to solve problems creatively. The TRIZ theory is based on scientific sound tools that allow the generation of innovative ideas and facilitates the design of new and improved products and processes, no matter the technology field. TRIZ is based on the premise that creativity means finding a standard solution based on the fact that somebody somewhere has already solved the problem or one similar to it, and adapting it to the current problem meaning that almost each anthropogenic system has its predecessor, also created by people. However, TRIZ is so powerful that can be applied at studying both anthropogenic, and not anthropogenic systems as well as social systems as the laws of overcoming of contradictions at their development are identical. Behind TRIZ philosophy some real world regularity stands functioning in anthropogenic as well as in non-anthropogenic world.

TRIZ has been used in industrial practice since its development in the 50s of the last century. There are several books that introduce the basics of TRIZ tools from a practitioners perspective (e.g. Terninko et al., 1998, Savransky, 2000, Hipple, 2012).

It is well known that processing industries commonly use TRIZ to solve their design and operational problems. However, the chemical and process engineering journals have seldom published papers dealing with the methods supporting engineering creativity (Kraslawsky et al., 2015). The aim of this paper is to present an approach that integrates TRIZ and MACBETH for the selection of an improved chemical design among different options. Section 2 briefly describes what is the theory of TRIZ, the contradiction matrix and its solving process as well as the applications of TRIZ in chemical process industries. Section 3 describe the MACBETH, a multiple criteria decision analysis (MCDA) method that allows the evaluation of options against multiple criteria, as well as the main steps of the approach. Section 4 presents a framework for combining TRIZ and MACBETH in systematic innovation. Section 5 presents the case study, and describes the procedure used to combine TRIZ and MACBETH in order to select the best option. The last section of the paper, section 6 summarizes the relevant results as well as the main conclusions of the work.

2. What is TRIZ?

2.1 General presentation

TRIZ is the Russian acronym for Teoriya Resheniya Izobreatatelskikh Zadatch and is a systematic process for invention, also called theory of inventive problem solving (TIPS) and was developed in the late 1940s by Genrich Altshuller and his colleagues in the former USSR (Yang and El-Haik, 2009). Genrich Altshuller, a Russian scientist and engineer, studied a large amount of technology patents, and from them drew out certain regularities and basic patterns, which governed the process of solving problems, creating new ideas and innovation. Using the knowledge from the analysis of patents the approach solves technical problems and presents innovative solutions meaning that creativity for innovation may be seen as a structured systematic method. The TRIZ problem solving process is based on five key different fundamental concepts (i.e. ideality, functionality, resource, evolution, and contradictions). Based on these key concepts TRIZ developed a system of methods. These concepts are the pillars of a variety of tools used in TRIZ and these elements make TRIZ distinctively different from other innovation and problem solving strategies.

According to TRIZ a challenging problem can be expressed as either a technical contradiction or physical contradiction. A technical contradiction takes place when there are two parameters of the system in conflict, and the improvement in the value of one parameter worsens the value of the other. Technical contradictions are solved by the application of the contradiction matrix, by the identification of the contradictions between the technical parameters (Srinivasan and Kraslawski, 2006). Another kind of contradictions, physical contradictions, takes place when a parameter should simultaneously have two different values occurring when two incompatible requirements refer to the same element of the system. Physical contradictions are removed by applying the four principles of separation, which are separation in space, separation in time, separation within a whole and its parts, as well as separation upon conditions (Orloff, 2006).

When in presence of technical contradictions TRIZ identify, and eliminate them in technical systems instead of trying to find a compromise or making the trade-off between the objectives. In fact, when analyzing the vast number of patents Altshuller detected that the best engineering solutions were obtained by removal of trade-offs between the objectives. According to TRIZ, a problem is solved if a technical contradiction is recognized and eliminated. The simplified TRIZ approach for creative problem solving is described in Fig. 1.

The application of the basic principles is made as shown in Fig. 1. This diagram is widely used in TRIZ literature and represents a simplified schema of a generic problem solving reflecting the idea that inventiveness can be easily understood and developed in a systematic way. The skill to solve problems is essential in any innovation process but the standard procedure to deal with them is mainly to use a trial and error procedure despite the existence of other approaches, namely TRIZ that support the idea that inventiveness can be easily understood and systematically developed. Many problem solvers try going directly from problem to solution through trial and error. Looking at an analogous general problem and its associated general solution is a more efficient approach.

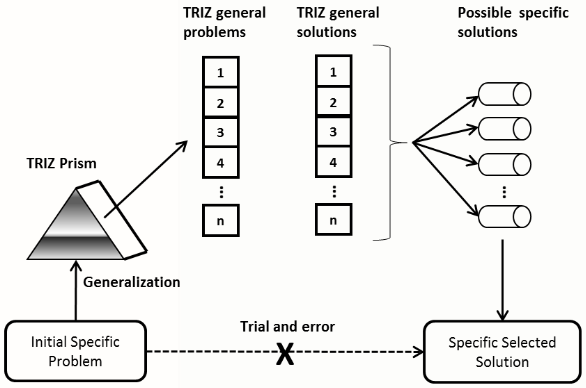


Fig. 1 TRIZ approach to problem solving.

The first and main task, step 1 is to identify the specific factual problem, and then step 2 comprises the formulation of the problem in the terms of a technical contradiction that is the basis of the TRIZ contradiction method. Step 3 is devoted to the search for a previously well-solved problem based in the matrix of contradictions. Altshuller identified 39 technical characteristics, which cause a conflict and named them the 39 engineering parameters. A 39 x 39 matrix is defined by the 39 engineering parameters that shows which of the 40 inventive principles other engineers and scientists have previously successfully used to solve contradictions similar to the ones being analysed. Step 4 consists in looking for parallel general solutions where G.S. Altshuller extracted 40 inventive principles, which are hints to find specific solutions to the technical problem to solve. The solutions to any contradiction are all the ways Altshuller discovered to eliminate technical contradictions. Therefore, based on the TRIZ method, one can easily find a number of potential solutions to the problem (Mann, 2002). Based on the TRIZ general solutions it is possible to envisage different specific solutions in order to pick the right solution to the problem. This is somewhat different from the trial and error procedure usually used by intuitive methods where the searching for problem solutions depends on a large quantity of possible ideas and the quantity of possible ideas the premise for the possibility of finding solutions with good quality.

2.2 Solving Technical Contradictions

The contradiction analysis is a powerful method of looking at the problem with new eyes. Once the reader understood this perspective the contradiction table becomes an important tool for generating several solution concepts. The contradiction matrix and the 40 inventive principles offer clues to the solution of the problems (Terninko et al., 1998). When using the contradiction table and the 40 principles the following simple procedure may be helpful:

1. Set the contradiction to solve;
2. Decide which feature to improve, and use one of the 39 engineering parameters in the contradiction table to standardize or model the feature. To use the table, one must go down the left hand side of the table until identify the standardized property to improve.
3. Then think about the features that degrade or get worse when you try to do this, and find this feature on the X axis.
4. For these two features (or more) identify the inventive principles in the intersection of the row (attributes improved) and column (attribute deteriorated) to resolve the technical contradiction.
5. Traduce the inventive principles into specific solutions, operational solutions that will solve the problem.

The contradiction matrix maps the most promising principles to contradictions in any pair of attributes. A section of the classical contradiction matrix is displayed in Fig. 2.

Improving Feature \ Worsening Feature		Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary object	Volume of moving object	Volume of stationary object
		1	2	3	4	5	6	7	8
Weight of moving object	1	+		15, 8, 29 ,34		29, 17, 38, 34		29, 2, 40, 28	
Weight of stationary object	2		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2
Length of moving object	3	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35	
Length of stationary object	4		**35, 28, 40 ,29**		+		17, 7, 10, 40		35, 8, 2, 14
Area of moving object	5	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4	

Fig. 2 Section of a classic contradiction matrix (adapted from Terninko et al., 1998).

For example, if one needs a static object to be longer without becoming heavier, this is a contradiction that according to the contradiction matrix can be solved with inventive principles 35 – parameter changes, 28 – mechanics substitution, 40- composite materials and 29-pneumatics and hydraulics.

It is usual to formulate several contradictions for one problem and form a set of recommended principles and use those principles which were identified more than once. The application of a pareto analysis allows the identification of a small number of principles that were recommended more times allowing to separate the vital few from the trivial many. The approach helps to understand and to document the technical contradictions in the system that may be of high importance for problem analysis.

2.3 The application of TRIZ in chemical process industries

The applications of TRIZ are abundant in industry. Spreafico and Russo (2016) analysed more than two hundred papers about TRIZ applications covering a large spectrum of industrial sectors with a high number of applications in mechanical engineering, automotive, electronics, energy and electrical, home appliances, and with less expression sectors like biomedical, chemical or textile just to name a few. Poppe and Gras (2002) highlight that TRIZ is and will be successfully applied in the process industry and that its adoption for solving problems in the process industry would benefit a lot if more case studies would be published. Despite significant achievements and several success stories and technological developments occurred in quite a lot of industries a lot of work needs to be done to generalize the use of TRIZ in chemical engineering (Ferrer et al., 2009, Rahim et al., 2015). However, the applications in chemical engineering are growing as displayed by the statistics of application of TRIZ presented by Abramov et al. (2015) concerning the chemical and chemical engineering industries. Some chemical engineering successfully examples, applied on specific problems of the chemical process industry, include a multi drum filter used in a textile application (Carr, 1999), a novel heat exchanger (Busov et al., 1999) the fluidized bed combustion boiler (Lee et al., 2002), the application of physical-chemical properties of bentonite (Teplitskiy et al., 2005) or the conception and development of a chemical product (Mann, 2005). Some authors refined the generic principles of TRIZ and enriched them with specific domain knowledge. That is the case of Srinivasan and Kraslawski (2006) who illustrate the application of the modified TRIZ to the design of inherently safer chemical processes. Since the book of Altshuller et al. (1998) with the list of 40 principles with technical examples for an explanation of the 39 engineering parameters, some authors give examples of the principles in various domains. Some authors presented the 40 inventive principles for chemical engineering (e.g. Grierson et al, 2003; Hipple, 2005; Robles et al., 2005) with the main goal of overcoming some difficulties experienced by chemical engineers due to the abstract level of the original inventive principles. Kim et al. (2009) developed a modified method of TRIZ to improve safety in chemical process design justified by the difficulty to access chemical process safety. The topic of innovation is of vital interest for chemical industries not only to improve competitiveness and increase benefits but also to account for the new challenges of sustainable production (Klatt and Marquardt, 2009).

A systematic and reliable methodology is needed for chemical engineers to bring innovation for their products and processes and TRIZ will be very helpful allowing people to remove the psychological inertia and expand their thinking (Bechermann, 2014).

The research work regarding the application of TRIZ to chemical and process engineering problems is recently proliferating in the literature (e.g. Pokhrel et al., 2015, Rahim et al., 2015).

3. MACBETH

Measuring the attractiveness of options by a Category-Based Evaluation Technique is the goal of MACBETH. The key distinction between MACBETH and other Multiple Criteria Decision Analysis (MCDA) methods is that it needs only qualitative judgements about the difference of attractiveness in order to help the decision maker quantify the relative value of the options/solutions and to weight the criteria used to evaluate the options/solutions. The approach, based on the additive value model, aims to support interactive learning about evaluation problems and the elaboration of recommendations to prioritize and select options/solutions in individual or group decision-making processes. Several applications of MACBETH approach cover areas like energy with project prioritization and selection (Bana e Costa *et al.* 2008), or Technology choice (Burton and Hubacek 2007, Montignac *et al.* 2009), areas like environment with landscape management (Soguel *et al*., 2008), risk management (Bana e Costa *et al.* 2008, Dall'Osso *et al.* 2009, Joerin *et al.* 2010) or water resource management (Bana e Costa *et al* 2004). Also in the public sector, there are many applications of MACBETH like in project prioritization and resource allocation (Mateus *et al.* 2008, Oliveira and Lourenço, 2002) or in engineering education for sustainability (João and

Quadrado, 2014) just to mention some of the many examples of the literature. MACBETH is a good approach to use in systematic innovation mainly to select a specific solution among different specific concepts because the approach is useful in any problem related with prioritization and selection of options.

MACBETH relies on a pairwise comparison questioning mode to compare the options, two at a time, and introduces seven qualitative categories of difference of attractiveness. Is there no difference or is the difference very weak, weak, moderate, strong, very strong, or extreme? The MACBETH value elicitation procedure is comprised of an input stage to elicit a consistent set of qualitative pairwise comparison judgements of difference in attractiveness and an output stage to construct an interval value scale from the set of judgements which numerically measures the relative attractiveness of options (Bana e Costa et al., 2011). When a certain judgement is inconsistent with previous ones, MACBETH detects the problem and gives suggestions to overcome it (for details see Bana e Costa and Vansnick, 1999 and Bana e Costa et al., 2005). The key stages in a multicriteria decision aiding process supported by the MACBETH approach can be grouped in three main phases: structuring, evaluating and recommending. After the identification and clarification of the criteria, i.e. those objectives that will be used to evaluate the options, it is possible to use the MACBETH to appraise the options in terms of difference of attractiveness in each one of the criteria.

MACBETH uses a simple additive aggregation model

$$v(A) = \sum_{i=1}^{n} w_i v_i(A)$$
$$\text{with} \quad \sum_{i=1}^{n} w_i = 1,\ w_i > 0, \quad \begin{cases} v_i(good) = 100 \\ v_i(neutral) = 0 \end{cases} \qquad (1)$$

where $v(A)$ is the global score of the option A, $v_i(A)$ is the score of the option A according to criterion i and w_i (i=1,2,…, n) are the weights or scaling constants. Eq. (1) allows to obtain the scores of different options by multiplying the scaling constant of each criterion i by the value of the option according to the same criterion and summing up all the weighted partial values in order to select the option with higher score. In a multiple criteria evaluation context scoring the options on an interval scale within each criterion is important because it permits one to meaningfully take a weighted average of each option´s scores on the criteria. The weights of the criteria can also be derived applying the MACBETH procedure (Bana e Costa and Vansnick, 1997). M-MACBETH is the multicriteria decision support software that implements the MACBETH approach. The software allows model structuring through a representation module where the criteria are commonly organized in a tree structure normally referred to as a "value tree". It also permits the construction of criteria descriptors, the development of value functions, the weighting of criteria, the scoring of options in relation to criteria, and extensive sensitivity and robustness analysis about the relative and intrinsic value of the options in face of several sources of uncertainties (http://www.m-macbeth.com).

4. Combining TRIZ and MACBETH in systematic innovation

In this work, we propose the use of a systematic innovation approach that combines the theory of inventive problem solving (TRIZ) and a multicriteria decision aid method MACBETH for the selection of an option solution among different option concepts. The goal is to highlight the possibilities of the synergy between TRIZ and MACBETH with a mere chemical engineering example. The objective is to convert the chemical engineering problem into a contradiction matrix and solving the contradictions through the TRIZ inventive principles. This might lead to various options or different specific solutions. In order to evaluate the different options against multiple criteria the MACBETH will be used as a selection method for the specific solutions obtained through the TRIZ approach to problem solving. The combined approach is depicted in Fig. 3 and includes the following main steps:

Step 1 – Identification of the specific chemical engineering factual problem that is of concern.

Step 2 – Looking at the problem through the TRIZ prism and making the generalization in order to formulate the problem in the terms of a technical contradiction.

Step 3 – Involves the search for previously well-solved problems based in the matrix of contradictions. In this step the general problems are identified as well as the improved features and features that get worse. At the end of this step the contradictions for the problem are identified.

Step 4 – Look for the general solutions based on the 40 inventive principles.

Step 5 – Based on the general solutions some specific solutions are developed (options to evaluate) and after they must be evaluated for the selection of the best specific solution among different specific concepts.

Step 6 – Structuring consists in the identification of the evaluation criteria, used to appraise the options, that usually are represented in a tree structure normally referred to as a "value tree".

Step 7 – Evaluating involves the determination of the criteria weights and the aggregation procedures to use in order to score the options or specific solutions to evaluate.

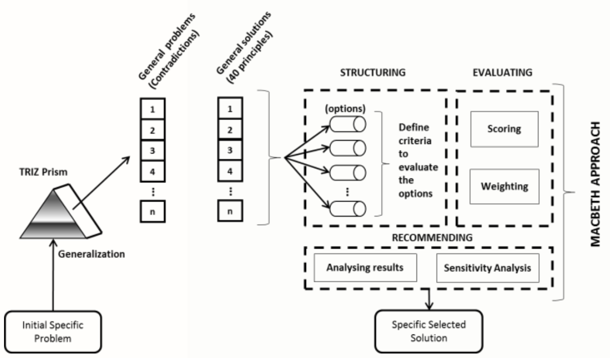


Fig. 3 Framework for combining TRIZ and MACBETH in systematic innovation.

Step 8 – Recommending is the last step in order to select the best specific solution. It includes the exploration of the model results, analysing the results, and performing sensitivity and robustness analysis of the model results.

5. The Case study

Distillation processes involve mass transfer between a liquid phase (or two liquid phases) and a vapour phase flowing in counter current fashion. The vapour and liquid phases are generated by vaporization of a liquid stream and condensing a vapour stream, which in turn requires heating and cooling. Distillation is thus a major user of energy in the process industries and globally. A "simple" distillation column is defined as one in which a single feed is separated into two products, where the column has a single reboiler and a single condenser. A number of operational problems can reduce energy efficiency of a distillation process (Jobson, 2014). In the design of continuous distillation columns one of the things that is crucial for a good operation is the selection of the type of reboiler. During the normal operation of a distillation column, depending of the type of products to evaporate, it is usual to have some type of fouling in the reboiler that can reduce heat transfer rates, increasing steam demand or requiring steam at higher temperatures. A high pressure drop may indicate fouling of the reboiler with an associated increase in heating and cooling duties.

In the design of the reboiler is common to consider some extra heat exchanger area to account for this type of problem, and during the time of operation the amount of steam used to maintain the same rate of boiled products need to be increased. After some point, it is impossible to maintain the rate of boiled products and it is necessary to stop the operation in order to clean the reboiler. One possibility to maintain the column in operation requires backup redundancy in the reboiler, meaning the need to have an identical secondary reboiler to back up the primary unit implying investment costs in a reboiler that usually is out of service.

When choosing the configuration of the reboiler we can start from the simplest and less expensive reboiler, the thermosiphon horizontal reboiler (TSH-Reb), a very common type of reboiler used in refining applications. This reboiler is a horizontal mounted shell and tube exchanger, with the boiling fluid on the shell side. Traditionally the TEMA type X, G or H shells have been used for this purpose. The principal advantages are the multi-pass arrangements for the heating fluid and a differential expansion that can be easily accommodated. Considering a process fluid with propensity to fouling, and having in attention the fact that the process fluid pass in the shell side, the cleaning process will be difficult and the mechanical cleaning can only be done by removing the bundle. This operation can take some time due to the difficulty of the cleaning process.

Understanding how to structure the problem as a contradiction is an essential step in the analysis.

The problem here consists in finding a solution that allows longer operation of the reboiler, when the process fluid have tendency to form a fouling, maintaining the same rate of boiled products without the need to stop for maintenance.

What is the goal of the system? Increase the time of operation; improve the ebullition rate; reduce the number of maintenance stops; and reduce the energy consumption (steam). In this work, we used the table of conflicts between the 39 design parameters and the 40 generic principles used in contradiction analysis as described in Terninko *et al*. (1998).

There are several degrading parameters associated with each improvement that need to be identified. In the Table 1 we present the parameters that degrade (worsening feature) when a parameter (improved feature) is improved, extracted from the TRIZ contradiction matrix, and the corresponding inventive principles used to reduce the contradiction. The information was taken from the intersections of the relevant parameters on the contradiction table, the 39x39 matrix of engineering parameters.

The identification of the contradiction allowed the enumeration of the inventive principles to take into considerations. A tally of the principles suggests looking at those that occur most frequently. The top inventive principles are presented in Fig. 4.

Table 1 Resume of the analysis of the TRIZ contradiction matrix.

Improved feature	Worsening Feature	Inventive principles
16. Duration of action by a stationary object	30. Object affected harmful factors	17;1;40;33
22. Loss of energy	6. Area of a stationary object	17;7;30;18
	25. Loss of time	10;18;32;7
25. Loss of time	6. Area of stationary object	10;35;17;4
	19. Use of energy by moving object	35;38;19;18
	22. Loss of energy	10;5;18;32
	27. Reliability	10;30;4
	30. Object affected harmful factors	35;18;34
	31. Object generated harmful factors	35;22;18;39
	33. Ease of operation	4;28;10;34
39. Productivity	6. Area of a stationary object	10;35;17;7
	30. Object affected harmful factors	22;35;13;24
	31. Object generated harmful factors	35;22;18;39

The analysis of the inventive principles of Fig. 4 shows that the inventive principle 18 (Mechanical vibration/oscillation) and 35 (Transformation of the physical and chemical states of an object, parameter change, changing properties) have the higher frequency of occurrence (seven times). Principle 10 (Prior action) is chosen six times, the principle 17 (Moving to a new dimension) is mentioned four times while the inventive principles 4 (Asymmetry), 7 (Nesting) and 22 (Convert harm in to benefit) are recommended three times.

Based on the general solutions extracted from the list of inventive principles it is possible to identify some specific solutions that improve the performance of a reboiler.

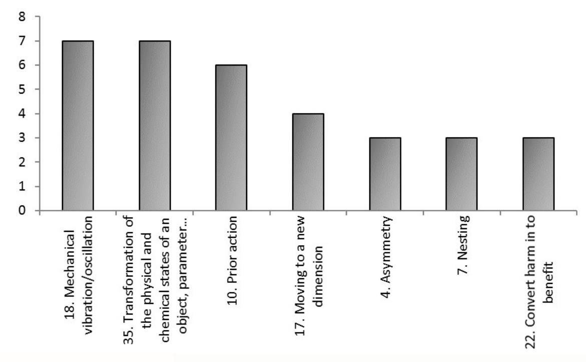


Fig. 4 The frequency of inventive principles recommendations.

According to the interpretation of the inventive principle 17 – "Moving to a new dimension", one of the solutions pointed out is the tilt or reorientation of the object. That means, if we change from a horizontal thermosiphon reboiler (TSH-Reb) to a vertical thermosiphon reboiler (TSV-Reb) the formation of fouling would be reduced. This transformation also implies that the process fluid pass inside the tubes instead of the shell side to improve the heat transfer coefficients and the speed of the process fluid is increased compared to the horizontal one. This situation implies also a single pass in the tubes that contributes to an easier mechanical cleaning. In a vertical thermosiphon reboiler (TSV-Reb) the mechanical cleaning of the tube side is more easy than the cleaning of the horizontal one.

The inventive principle 18 – "Mechanical vibration/oscillation" suggests the use of a type of dispositive that promotes some type of vibration contributing to the reduction of the fouling formation. In recent years, we can find in the literature some devices used in heat exchangers to reduce the formation of fouling (Hasanpour et al., 2014, Sheikholeslami et al., 2015, Zhang et al., 2016). Thus, tube inserts are used to simultaneously carry out two functions: enhancing the turbulence in the throughput flow (increase the Reynold's number), and inhibiting the rate of deposition through mechanical action as well as restricting it to a lower level. This means that the use of tube inserts improves the heat transfer efficiency by cleaning up the existing fouling and avoiding the fouling formation making possible the improvement of heat transfer efficiency. A forced circulation vertical reboiler with inserts (FCVI-reb) is a specific solution that could be obtained making use of the principle 18.

According to the inventive principle 4 – "Asymmetry" the suggestion is transforming the design of the reboiler in a way that the symmetry is changed. Nowadays some reboilers manufacturers (ex. Koch Heat Transfer Company) suggest the use of reboilers with twisted tubes. The twisted tubes reboiler (TTH-reb) is a specific solution that could be obtained making use of principle 4. The special arrangement of this tubes avoid the use of baffles in the shell side. By this way, the turbulence of the fluid is maximized in the tube and shell sides, improving the heat transfer coefficient, and reducing the fouling formation.

According to the inventive principle 10 – "Prior action" the suggestion is to resolve the cause of the fouling before the reboiler, i.e. before the process fluid enters the distillation column. In some cases, this approach can resolve partially the problem of fouling, but in other cases the fouling formation is directly related to the operating temperature of the reboiler.

After looking for the general solutions based on the 40 inventive principles and having decided on the specific solutions that overcome the problems the next step consists on the evaluation of the solutions and the selection of the best specific solution among different specific concepts. The selection of the solutions can be viewed as a multicriteria decision problem where the options are evaluated against multiple criteria.

The options to evaluate are: the thermosiphon horizontal reboiler (TSH-Reb), the thermosiphon vertical reboiler (TSV-Reb), the forced circulation vertical reboiler with inserts (FCVI-reb) and the twisted tube reboiler (TTH-reb).

The MACBETH socio-technical approach was used in order to evaluate the options against multiple criteria making use of qualitative judgments about the difference of attractiveness between two elements at a time in order to generate numerical scores for the options in each criterion and also to weight the criteria. The process began with the elicitation of the key aspects that the decision maker considered to be the criteria by which the attractiveness of any option should be appraised. A value tree was then created in the M-MACBETH decision support system along with the introduction of the reboiler options into the model, according to Fig. 5.

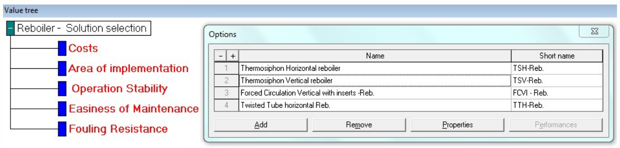
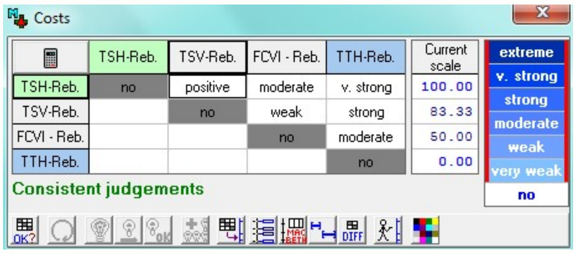


Fig. 5 Value tree and reboiler options.

The options were then ranked in order of their attractiveness in terms of costs. Next qualitative judgements regarding the difference of attractiveness between the options were elicited based on the qualitative categories “very weak”, “weak”, “moderate”, “strong”, “very strong” and “extreme. From the completed consistent matrix of judgements MACBETH created a numerical scale (see the matrix of judgements in Fig. 6)

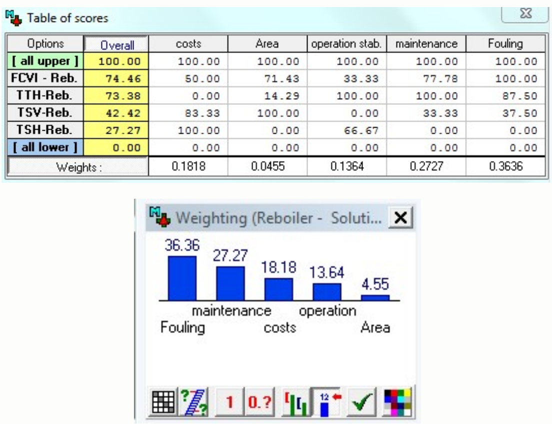


	TSH-Reb.	TSV-Reb.	FCVI - Reb.	TTH-Reb.	Current scale
TSH-Reb.	no	positive	moderate	v. strong	100.00
TSV-Reb.		no	weak	strong	83.33
FCVI - Reb.			no	moderate	50.00
TTH-Reb.				no	0.00

Fig. 6 Matrix of judgements and MACBETH value scale for costs.

The process was then repeated to create value scales for the remaining criteria (all of the scores can be found in Fig. 7). The next step was to weight the criteria in order to allow the calculation, by an additive model, of the overall score for each option. A comprehensive explanation and discussion about the weighting procedure of MACBETH approach is presented in Bana e Costa et al., (2011) and the histogram with the weights of the criteria presented in Fig. 7. A table with the partial and global scores was then created allowing to see the final results of the model (see Fig. 7). The most attractive option is the forced circulation vertical reboiler with inserts (FCVI-Reb) given the decision maker´s judgements. The overall scores clearly show that the option twisted tube horizontal reboiler (TTH-Reb) is almost as attractive has the most attractive option.

The sensitivity analysis on the weight of the criterion fouling (i.e. the criterion with higher weight) shows that if the weight of the criterion fouling goes bellow 30,3% than the option twisted tube horizontal reboiler (TTH-Reb) becomes more attractive than the option forced circulation vertical reboiler with inserts (FCVI-Reb) according to the information displayed in Fig. 8.



Options	Overall	costs	Area	operation stab.	maintenance	Fouling
[all upper]	100.00	100.00	100.00	100.00	100.00	100.00
FCVI - Reb.	74.46	50.00	71.43	33.33	77.78	100.00
TTH-Reb.	73.38	0.00	14.29	100.00	100.00	87.50
TSV-Reb.	42.42	83.33	100.00	0.00	33.33	37.50
TSH-Reb.	27.27	100.00	0.00	66.67	0.00	0.00
[all lower]	0.00	0.00	0.00	0.00	0.00	0.00
Weights :		0.1818	0.0455	0.1364	0.2727	0.3636

Fig. 7 Table of scores and histogram of criteria weights.

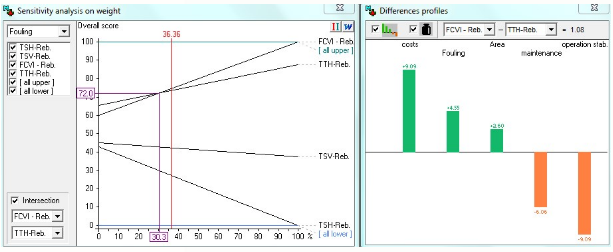


Fig. 8 Sensitivity analysis on weight of criterion fouling and difference profiles of TTH-Reb and FCVI-Reb.

Looking at the differences profiles of the options FCVI-Reb and TTH-Reb we can observe that the criteria that punish the option FCVI-Reb is the maintenance and the operation stability while the costs and fouling are the criteria that are in favor of the option FCVI-Reb. The M-MACBETH software allows for numerous sensitivity analysis to be performed. We will not describe them here but for more information about sensitivity and robustness analysis see Bana e Costa et al. (2012).

6. Conclusions

In order to successfully assist chemical engineers in solving problems a combined strategy using TRIZ and MACBETH was established. The product and process innovation can be achieved in a sound scientific way and the synergies of the combined approach were highlighted with a chemical engineering example. The case study is related with distillation which is very important process unit in chemical process industry because most chemical processes require separation of chemical mixtures, and distillation is widely used. Distillation is also a major user of energy in the process industry, reason why it is very important to reduce the operational problems that can reduce the energy efficiency of a distillation process. The focus of the case study was on the type of reboiler because one of the things that is crucial for a good operation is the selection of the type of reboiler due to problems of fouling that can occur and are responsible for the reduction of heat transfer rates increasing steam demands.

The case study illustrates the effectiveness of MACBETH approach in order to support TRIZ methodology. TRIZ was essential to achieve the specific solutions with simplicity but displaying the distinctive way of thinking in TRIZ methodology making people think beyond their own experience reaching across disciplines to solve problems.

The MACBETH approach can be very helpful in the subsequent steps in order to select the specific solution. To make the selection it is necessary to identify the evaluation criteria used to appraise the specific solutions and determine the criteria weights and aggregation procedures in order to score the solutions. The use of MACBETH to perform the selection can be seen as an advantage due to the simplicity of the pairwise comparison questioning mode to compare the solutions. The multicriteria decision support software M-MACBETH also allows sensitivity and robustness analysis to be easily performed. The scheme of TRIZ combined with a multicriteria decision analysis method, such as MACBETH is very useful and can be addressed by engineers as well as researchers interested in creativity research and its practical implementation.

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