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Decision support for energy savings and emissions trading in industry

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A B S T R A C T

LifeSaver project congregates the development of contextualized decision support approach for energy savings and emissions trading. This approach aims at supporting industrial users in selecting the best alternative to ensure minimization of energy consumption during the production process as well as support to emissions trading market. LifeSaver provides decision support for: (i) immediate reaction and (ii) process reconfiguration and Emission Trading System. This categorization serves as base for defining the methods to be applied. The support for immediate reaction uses Case-based Reasoning together with probabilistic analysis. Process reconfiguration and ETS is implemented through the use of multi-criteria decision analysis based on MACBETH method, which has been adapted for LifeSaver specific characteristics. The paper proposes categorization of approaches, main criteria involved in the process and associated algorithms. Moreover the approaches proposed were successfully tested in industrial environment and the results obtained are here presented.

1. Introduction

Many organizations view energy as an escalating, uncontrollable cost when, in reality, energy consumption can be controlled by acquiring new, more efficient technology (Zobler and Sauchelli, 2009) and through behavioural modifications (Kastner and Matthies, 2014). The need to reduce the energy intensity of production and corresponding greenhouse gas emissions is acknowledged, but there are significant technical and non-technical barriers to achieving this (Walsh and Thornley, 2012). The greatest perceived barriers are the perception of the lack of resources to be devoted to improving energy efficiency, and the existence of other priorities such as the importance of guaranteeing business continuity (Trianni et al., 2013).

Pons et al. (Pons et al., 2013) concluded that the use of energy and material saving technologies does not have a clear and significant relationship with economic performance although a significant positive relationship is found between energy and material saving technologies and environmental performance.

Yet, rising energy prices, and customers' increasing ecological awareness have pushed energy efficiency to the top of the agenda (Bunsea et al., 2011). Moreover, and even under very demanding values of payback period the margin of improvement of the CO_2 emissions is around 20% (Moya and Pardo, 2013).

The implementation of measures to increase energy efficiency in industrial companies are becoming a key aspect and the importance of having a comprehensive view of the systems when making such changes in industry is widely recognized both from management (Sandberg and Söderström, 2003) and administrative point of view (Simon, 1997) together with environmental perspective (Morjav and Gvozdenac, 2008). This aspect is crucial, as industrial systems form complex relations both within the industrial equipment at plant level and in the interaction with their surroundings. In fact complicating factors, such as complex industrial sites and energy flows, multiple products and fuels, and the influence of production rate on energy efficiency, contribute for the need of adopting a structured framework to define and measure energy efficiency more precisely (Giacone and Mancò, 2012). Thus, the development of computer-based decision support increases the possibility to make adequate analyses as required of different complex systems (Karlsson, 2011).

The recommended business practice (Morjav and Gvozdenac, 2008) for industrial companies is to actively participate in energy efficiency programs, monitor energy consumption, emissions and raw material usage using an auditable system, manage the CO_2 emissions and position using a simple trading system and finally integrate previously mentioned activities in one decision support system to eliminate operational risk, investment and trading exposure.

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Research shows that there are still much room for energy efficiency improvement and among the approaches that prove to be succeeded are the ones implemented using process integration[1] (examples can be found in (Friedler, 2010) and (Klemeš and Lam, 2011)). In the context of energy efficiency this process is commonly known by "pinch analysis" which refers to a technique for designing a process to minimise energy consumption and maximise heat recovery, also known as heat integration, energy integration or pinch technology). Widely used pinch-based methodologies are based on Total Site concept, combining aspects so diverse as: utility heating and cooling requirements of individual processes (Vrbanov et al., 2012), collaboration between different companies ((Hackl et al., 2011), (Hackl and Harvey, 2013)), process simulation, exergy concepts (Hackl and Harvey, 2012), etc. Chew et al. (Chew et al., 2013) provide an overview of the issues that must be considered for total site heat integration from an industrial point of view.

Nonetheless, even enterprises with advanced management systems rarely monitor efficiency of energy usage and materials flows within their processes, thus having difficulty to effectively manage their resource efficiency (Dobes, 2013). To achieve the desired efficiency improvements, energy use should be measured in more detail and in real-time, to derive an awareness of the energy use patterns of every part of the manufacturing system (Vikhorev et al., 2013).

In recent years, the development of decision support methods for energy savings has been strongly oriented for the application in building energy efficiency. For this the European energy policy has contributed with its clear orientation towards the preservation of energy and the improvement of indoor environmental quality in buildings through the adoption of the European Commission's (EC) Energy Performance of Buildings Directive (European Community, 2003). To this end, in the past decades, there have been significant efforts towards designing, operating and maintaining energy efficient and environmentally conscious buildings (Kolokotsa et al., 2009). Examples of this research are provided by Martinaitis et al. (2007), Kolokotsa D. (2007), Wong and Li (2008), and Campos and Neves-Silva (2011). Additionally, some research has been conducted in the development of decision support systems for environmental management ((De Benedetto and Klemeš, 2009), (Khalili and Duecker, 2013)).

Some of the concepts used for energy efficiency in buildings can be applied in the industrial sector but truth is that specificities of the problems are not the same. Thus, methods specifically developed for the industrial problem are quite few and are mainly based in modelling and simulation of the industrial facility and do not consider important aspects such as keeping the values of the decision-making criterion close to normal business conditions (Moya and Pardo, 2013).

The overall objective of the LifeSaver project (LifeSaver Consortium, 2012) is to develop a methodology and platform to support companies in optimising their operations and enabling them to increase energy savings and decrease CO_2 emissions. This paper describes the results achieved by the project regarding algorithm research on decision support for energy savings and emissions trading.

Authors start by introducing the topic describing the background, the objectives and the concept. Then the section on the *LifeSaver decision support approach* introduces the LifeSaver decision support approach categorization, and proposes the methods and algorithms to implement LifeSaver decision support approach. In this section the two methodologies developed to answer LifeSaver requirements are also proposed, i.e. the methodology to Support Immediate Reaction and the methodology to Support Process Reconfiguration and Emissions Trading System (ETS). Finally, conclusion section provides a summary of the key elements proposed within the paper and bridges the results obtained with the future work that needs to be developed.

With the aim to produce an industry-oriented platform, the business cases defined within the project have been analysed and the end users' expectations and requests have become necessary requirements for the LifeSaver platform. Combining the business and technical objectives for each business cases generic LifeSaver scenario has been generated.

Also, appropriate decision support enabling companies to increase their energy savings and decrease emissions have been analysed.

1.1. Background

The process of reaching a decision is called *decision-making process* and it begins when we need to do something but we do not know what. Therefore, decision-making is a reasoning process, which can be rational or irrational, and can be based on explicit assumptions or tacit assumptions. Decision-making is said to be a psychological construct. This means that although we can never "see" a decision, we can infer from observable behaviour that a decision has been made. Therefore, we conclude that a psychological event that we call "decision making" has occurred. It is a construction that imputes commitment to action. That is, based on observable actions, we assume that people have made a commitment to affect the action.

Structured rational decision-making is an important part of all science-based professions, where specialists apply their knowledge in a given area for making informed decisions. For example, medical decision-making often involves making a diagnosis and selecting an appropriate treatment. Some research using naturalistic methods show, however, that in situations with higher time pressure, higher stakes, or increased ambiguities, experts use intuitive decision making rather than structured approaches, following recognition primed decision approach to fit a set of indicators into the expert's experience and immediately arrive at a satisfactory course of action without weighing alternatives.

When trying to reach a decision, the main variation in the decision making process is related with criticality. This means that the process is affected by the urgency and by the risk associated to the situation. In fact, if the situation is critical it is highly unlikely to expect that the decision maker will follow the standard decision making process, step-by-step. In many situations decision makers choose to follow straightforward procedures, most of them intensively tested to ensure repeatability.

Within LifeSaver criticality is not a key issue, since the processes we are focusing on do not involve any kind of possible harm to people or installations. Yet, it is also true, that we have identified situations where it is important to have a decision in a short time frame whereas in other cases the idea is that the decision maker follows a specific step-by-step decision process, supported by the LifeSaver platform. To tackle these two different situations the LifeSaver decision support approach was developed and is here presented.

1.2. Objective and concept

The overall objective of the LifeSaver project is to develop a methodology and platform to support companies in optimizing

[1] Methodologies to combine several processes aiming the three-parted reduction: (i) consumption of energy; (ii) consumption of raw materials, (iii) negative environmental impact.

their operations and enabling them to increase energy savings and decrease CO_2 emissions. This support is in the form of a set of ICT building blocks that combine context awareness, ambient intelligence monitoring and standard energy consumption data measurement, providing:

- comprehensive information about the energy consumption to be processed in enterprise management systems, for the purpose of achieving significant energy savings,
- a knowledge-based decision support system for optimisation of energy performance of operations, and
- appropriate (almost) online and predicted cumulative data on the CO_2 emissions, as input for the decision support services to enable emission trading across industries and among companies.

LifeSaver complements currently measured energy consumption data with diverse information from ambient intelligent systems (e.g. interactions between human operators and machines or processes) and process-related measurements (e.g. temperature or oil level of a specific machine). The main objective is to enrich energy consumption data with information about the context in which the use actually occurred. This enables LifeSaver to access and process more complete information to target energy efficiency optimisation and CO_2 emission reduction. The monitored energy consumption enriched with context from ambient intelligence data, is the basis for the identification of energy profiles and energy consumption and emissions patterns. These profiles and patterns are then used to support decision-making in different situations. To this end, one of the main building blocks being developed in the scope of this project is a set of services to support decision-making. The complete approach and methodology used in the development of this building block is presented in the next sections. Fig. 1 presents LifeSaver concept (LifeSaver Consortium, 2012).

2. Decision support approach

LifeSaver Decision Support Services provide systematic mechanism to save energy in current operations and reduce CO_2 emissions. This kind of decision support needs to congregate aspects such as risk, costs, legal issues, etc. Their primary purpose is to validate that time, effort and money invested to reduce energy usage or environmental improvement in industry provides the expected results. As a consequence of reducing the energy consumption during the production process, it is important to understand the behaviour of the EU ETS in order to plan the strategic performance of companies.

To achieve the envisaged level of decision support the following functionalities must be provided to the user:

- Definition of "what-if" scenarios;
- Identification of alternative options for energy savings, emission reductions, improved efficiency in the raw materials usage;
- Identification of the best solutions for emission trading activities;
- Traceability of past decisions enabling the evaluation of the results obtained.

The implementation of risk analysis and multi-criteria decision-making techniques, using the information being provided by the other LifeSaver services, will enable the provision of the decision support envisaged. Note that, since Decision Support will be "at the output" of the LifeSaver process, all information available may be valuable and useful for decision (e.g. context extracted/processed, energy models selected, prediction models selected, prediction results, energy consumed/predicted, emissions calculated/predicted, etc.).

2.1. Categorization of LifeSaver decision support

The first thing to do when analysing the characteristics of the LifeSaver process is understanding when and how decision support

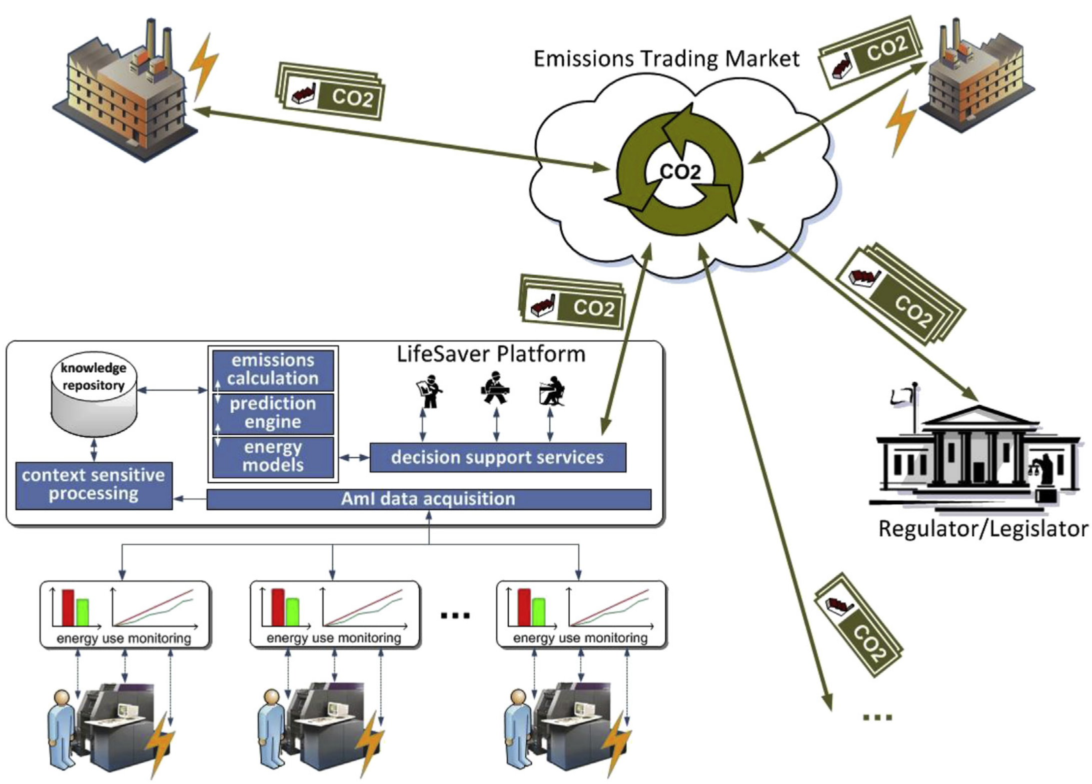

Fig. 1. LifeSaver concept.

is needed, which determines the type of approach that must be followed. Based on the proposition made by (Kolokotsa et al., 2009), LifeSaver will provide support in two different ways:

- Support for immediate reaction - involves the definition of a strategy to respond to an abnormal situation that must be normalised. This approach implies the application of a corrective measure based on real-time measurements;
- Support for process reconfiguration and ETS – involves the elaboration of scenarios to be evaluated in order to reach a decision about the best alternative. The approach is to be applied during operational phase but without interacting with production process in real time.

Due to their different characteristics the two approaches demand different methods:

- Immediate reaction approach: based on the paradigm of Intelligent Decision Support (Holsapple and Whinston, 2000) implemented through the use of Case-based Reasoning (CBR) together with probabilistic analysis;
- Process Reconfiguration and ETS approach: implemented through the use of multi-criteria decision analysis (MCDA), combined with simulation-based analysis when needed.

Fig. 2 presents the categorization of LifeSaver decision methodological approach according to their different characteristics.

2.2. Methodology to Support Immediate Reaction

One of the main research lines on decision support systems has evolved towards including intelligent abilities in those systems. These systems are based on artificial intelligence or intelligent agent technologies and are commonly called Intelligent Decision Support Systems (IDSS). Their main objective is to realize decision making functions by gathering and analysing evidence, identifying and diagnosing problems, proposing possible courses of action and evaluating the proposed actions representing some human brain competences. A solution that demonstrated to be quite successful is CBR. CBR systems are based on a starting set of cases that are structured in an appropriate format in order to constitute training examples. It is a problem solving approach that works by identifying commonalities between the target problem and retrieved cases.

2.2.1. Decision model

The approach proposed in LifeSaver is to combine CBR with probabilistic analysis in order to provide the user with a brief idea of which might be the result of following a specific course of action (Marques and Neves-Silva, 2011). This is made through the collection of information and data about the industrial plant along its operational phase. The idea is to collect information coming not only from the machines but also from experts that have deep knowledge on the specific production processes.

The following aspects must be covered:

- List of variables important to assess the overall energy consumption of the plant/machines;
- List of rules associated to the normal behaviour of the variables according with the current context;
- List of common causes for rule violation (i.e. abnormal energy consumption);
- List of possible alternatives (actions) to deal with the causes (i.e. restore normal energy consumption).

The initial modelling work must also include the definition of energy cost centres (ECC), which stand as the core elements of entire energy model of the industrial plant (Morjav and Gvozdenac, 2008). There are no fixed rules on how to setup model of ECCs as they can be any department, section or machine that uses a significant amount of energy or creates significant environmental impacts. However, the guiding principle for modelling setup is to follow the production process stages as given by the process flow chart for each industrial branch, and try to set the ECCs so that they coincide with existing production quantity control boundaries.

To avoid critical energy consumption values it is considered the observation of an energy consumption threshold for each ECC. When the thresholds are violated, a decision point is achieved and a set different alternatives must be considered: $A = \{A_1,\ldots,A_n\}$. The success of the applied alternative is measured in terms of time elapsed, Δt, between subsequent detections of abnormal energy consumptions for the same ECC. This time should vary accordingly with the alternative selected, and should be as long as possible to maintain the methodology objective.

In the proposed approach energy consumption is monitored and, in case there is an abnormal consumption, an event is generated. This event represents the need for an action to restore the normal energy consumption level. The event triggers a search for similar cases, which will result in a set of cases, and some of them could even be caused by different causes. The selection and

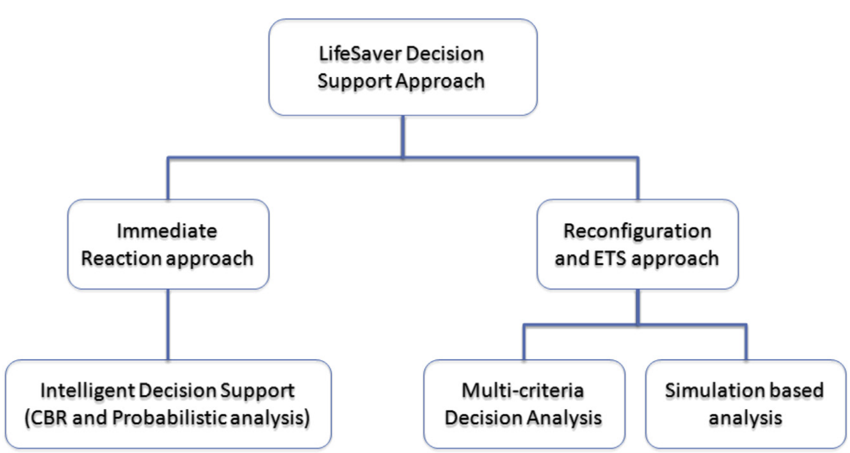

Fig. 2. Categorization of LifeSaver decision support methodological approaches.

elimination of the cause is made by providing the user with information on possible outcomes depending on the different alternatives that may be followed. The suggested alternative is the one that presents better cost/efficiency relation i.e. the cost associated to the number of similar decision processes that occurred along time, each time a specific pair (Cause, Alternative) was selected. Fig. 3 shows the proposed decision model using a Bayesian tree. In the tree this cost is given by $\mathrm{Co}(C_x, A_x)$ and is computed as follows:

- Check how many times that alternative was selected together with that cause, $n\_DP(C_x, A_x)$
- Compute the elapsed time between each situation
- Computed the averagecost:

$$\mathrm{Co}(C_x, A_x) = \frac{\mathrm{Co}(A_x) \times n\_DP(C_x, A_x)}{\Delta t(DP)} \tag{1}$$

where $\mathrm{Co}(A_x)$ is the cost of the alternative and $\Delta t(DP)$ is the accumulated time elapsed between decision processes that were solved with action proposed by alternative A_x.

In this approach the methodology seeks to congregate the effect of each alternative in the future energy consumption of the plant. This is done by following the probabilities attributed to each path. In the end, the solution will come in the form of an action to eliminate a cause, being that action the most cost-efficient for that cause, at that moment. The model was built following the logic of the problem, ensuring that, at each probabilistic node, probabilities along any outgoing branch sum one. The expected result is achieved by rolling the tree backward (i.e., from the leaves to the root). On the tree, the value of a node can be calculated when the values for all the nodes below it are available. The value of a node is the expected value of the nodes following it, using the probability of the arcs. The tree can grow in complexity considering the number of causes that might be involved as well as the number of possible alternatives that may be selected.

2.2.2. Decision algorithm for immediate reaction

The algorithm proposed is based on a twofold combination of probabilistic risk analysis and CBR. It is assumed that the combination of these two methodologies enables to identify the most probable cause of a problem as well as best strategy to eliminate it, to be followed, i.e. the most appropriate action to be executed.

The starting point is the analysis of the collection of previous cases, which represent the history of the system in terms of Events, Causes and Alternatives. Then, the probability of a specific cause is established by the number of previous cases, associated to an Event, whose source was proved to be that cause. On a second stage the time elapsed, between cases associated to the same Events and Causes, is used to estimate the effect that a specific Alternative may have on the system behaviour. Having this result the risk analysis is performed in order to identify the option with lower risk level in terms of costs.

The use of the methodology can be put in a step-by-step procedure, as follows:

1. Once an Event is detected, state vector $\boldsymbol{x}$ is generated, containing the set of state variables with relevant information for the characterization of the state of the plant in some particular instant of time when a *situation* is to be reported, such that:

$$\boldsymbol{x} = [x_1 \ldots x_n]^T \tag{2}$$

2. Collect all the cases, Ca, associated to the Event detected, E:

$$Ca(E) = \{Ca_1,\ Ca_2, \ldots, Ca_n\} \tag{3}$$

In this step, the methodology finds the stored cases, which present appropriate similarity characteristics with the current Decision Process, DP. Nearest-neighbour retrieval is a simple approach that computes the similarity, $\mathrm{Sim}(\boldsymbol{x}_i, \boldsymbol{x}_j)$, between stored cases and new input case based on weight features, w. A typical evaluation function presented by Kolodner (Kolodner, 1993) is used to compute nearest-neighbour matching:

$$\mathrm{Sim}\{Ca_i, DP\} = \mathrm{Sim}\left(\boldsymbol{x}^{Ca_i}, \boldsymbol{x}^{DP}\right) = \frac{\sum_{k=1}^{n} w_k \mathrm{Sim}\left(x_k^{Ca_i}, x_k^{DP}\right)}{\sum_{k=1}^{n} w_k} \tag{4}$$

3. Discard all the cases which similarity level is below a specified threshold. The remaining ones are considered using the similarity level,Sim $\{Ca_i, DP\} = w_i$ as a weighting value.
4. Collect all the Causes, C, of the remaining cases: $C = [C_1 \ldots C_n]^T$
5. Arrange the remaining cases in a matrix that relates Ca with C:

$$M_{CaC} = \begin{bmatrix} Ca_{1C_1} & \ldots & Ca_{1C_n} \\ \vdots & \ddots & \vdots \\ Ca_{nC_1} & \ldots & Ca_{nC_n} \end{bmatrix} \tag{5}$$

6. For each Cause calculate the probability of that Cause, C, to be the correct one, considering the similarity level of each case, w,

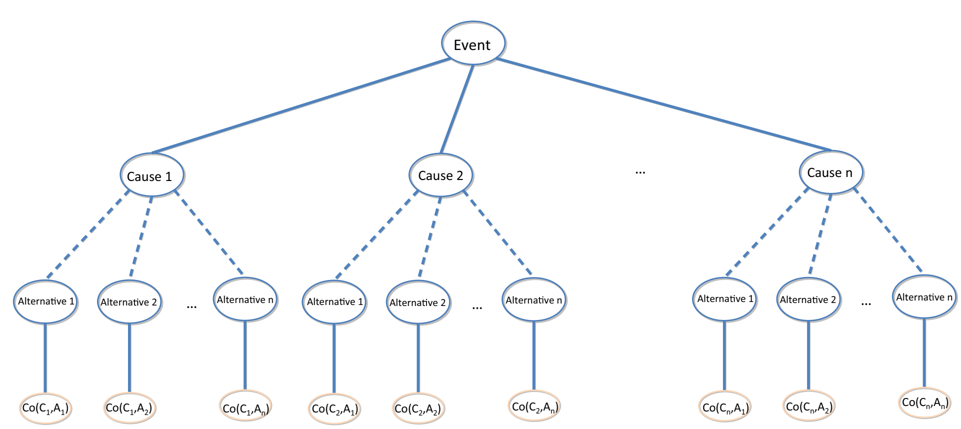

Fig. 3. Decision model for immediate reaction.

the frequency of the case, f, and the total number of cases associated to an Event, E, considering their frequency:

$$p(C|E) = \frac{\sum_{i=1}^{n} w_i f_i}{\sum_{i=1}^{n} f_i} \tag{6}$$

n – total number of cases associated to event E

7. Organize each element of M_{CaC} in chronological order from the oldest case to the most recent one.
8. Calculate the time elapsed, Δt_{Ca}, between two consecutive cases:

$$\Delta t_{Ca} = \text{Detection}(Ca_i) - \text{Detection}(Ca_{i-1}) \tag{7}$$

9. For each alternative compute the probability associated to the use of that alternative and the occurrence of a new Event, nE:

$$p(nE|A_i) = \frac{nCa_{A_i}}{n} \tag{8}$$

nCa_{A_i} – total number of cases which followed A_i

10. Calculate the costs of the action A_i diluted along the accumulated time:

$$\text{timeCost}(A_i) = \frac{nCa_{A_i} * \text{Cost}(A_i)}{\sum \Delta t_{Ca_{Ai}}} \tag{9}$$

11. Calculate the probable costs associated to A_i:

$$p\text{Cost}(A_i) = p(nE|A_i) \times \text{timeCost}(A_i) \tag{10}$$

12. Calculate the total probable cost considering the cause probability calculated in (6). Thus, for each cause, the total risk is given by:

$$\text{totalCost}(C_i) = P(C_i|S) \times \sum_{k=1}^{n} p\text{Cost}(A_k) \tag{11}$$

13. Select C_i that presents lower totalCost.
14. Select A_k that presents lower pCost.
15. Store the pair (Cause, Alternative) selected by the user.

The results aim at minimising the costs of intervention and for that reason the minimum cost is selected as the appropriate strategy to be suggested.

2.3. Methodology to Support Process Reconfiguration and ETS

As already explained, the characteristics of underlying project LifeSaver require the development of a specific strategy for decision support. When focusing on the methodology to Support Process Reconfiguration and ETS the first step consists of building scenarios to be compared. These scenarios will be build by the user, supported by the system, and when needed, using simulation capabilities. From a general point of view it is expected that the methodology will have to consider several criteria, which may vary from decision situation to decision situation. It is necessary to have information regarding how well a specific scenario fits a specific criteria set.

Each time there is a problem that involves the consideration of a finite number of criteria and alternatives, we are in the field of the so-called multi-criteria decision analysis. To solve this kind of problems decision makers normally use a number of techniques to support them in the identification, comparison and evaluation of the existing alternatives. This process is performed taking into consideration the diversity of criteria, which are, in most of the cases, conflicting ones. Three fundamental problems can be applied to the assessment of a set of alternatives A:

1. Choosing: choose the best alternative from A.
2. Sorting: sort the alternatives of A into relatively homogeneous groups, which can then be arranged in preference order.
3. Ranking: rank the alternatives of A from best to worst.

Multi-criteria decision analysis considers the three fundamental problems identified and, in the last decades, many multi-criteria decision analysis methods have been proposed for choosing and ranking.

When speaking about decision making in real world, especially if we are dealing with business world, many problems are still solved using a simple Cost-Benefit Analysis (CBA), which evaluates the costs and benefits of the alternatives on monetary basis. Nevertheless CBA has some problems in incorporating different factors (e.g. environmental impact) to improve the quality of decision-making. Thus different techniques that enable the aggregation of such factors have been developed. The approach here proposed includes a mix of quantitative criteria expressed by indicators, which are weighted accordingly with user preferences. In addition to this, a methodology for quantifying attractiveness within a criteria based on the one proposed by MACBETH (Measuring Attractiveness by a Categorical Based Evaluation TecHnique) method ((Bana e Costa and Vansnick, 1994), (Bana e Costa and Vansnick, 1995), (Bana e Costa et al., 2004)), is also used. The implementation of these two possibilities will provide the user with an increased level of authority.

2.3.1. MACBETH method modified

MACBETH method uses the concept of multi-criteria decision analysis (MCDA[2]) (Bana e Costa and Oliveira, 2012) and is based on multi-attribute value theory. The basic idea is to judge the performance of alternatives with respect to a set of decision criteria. The weighted global scores representing the overall attractiveness of the considered alternatives are computed using an additive aggregation model to rank the alternatives.

Here a step-by-step description of MACBETH method is provided:

1. Deciding the relevant decision criteria, which are expressed in the form of a value tree.
2. The performance levels, representing the possible performance of the alternatives with respect to a particular criterion, are entered.
3. Defining a set of reference levels for the performance of the alternatives with respect to that criterion.

It is to be noted that minimum two reference levels are required, one to be identified as upper reference level and the other as the

[2] MCDA are a set of techniques that are designed to investigate a number of alternatives having multiple criteria and conflicting objectives.

lower reference level (Bana e Costa et al., 2002). Each alternative needs to be assigned with a performance level score representing attractiveness of the alternative related to two reference levels: the upper reference level and the lower reference level.

4. Convert the ordinal performance scales into proportional cardinal scales.
5. Select the alternatives and their performance with respect to different criteria.
6. Obtain the global attractive scores and rank the considered alternative.

Regarding step 4, the performances of alternatives with respect to various criteria are expressed using two scales, i.e. cardinal and ordinal scale. The cardinal scales are represented in numbers and can be manipulated with the help of basic mathematical operators, like addition, subtraction etc. On the other hand, ordinal scales represent comparative positions (e.g. first, more, higher etc.), therefore, direct mathematical treatments of these scales are found to be difficult. As in case of multi-criteria decision-making (MCDM) methods performance of the alternatives with respect to all the decision criteria needs to be compared, mathematical treatments of the data are therefore essential. MACBETH provides a methodology to address this issue by arranging the performance levels in a ($n \times n$) matrix, where n is number of performance levels selected for that criterion. The performance levels are arranged in descending order of their importance from left to right and top to bottom. Further, the decision maker is asked to map the difference of attractiveness between ordinal performance measures of two alternatives at a time, because the comparison of alternatives is done based on difference of attractiveness instead of attractiveness itself. MACBETH method provides a way of mapping the difference of attractiveness using seven semantic scales as 'null', 'very weak', 'weak', 'moderate', 'strong', 'very strong' and 'extreme' (Bana e Costa and Chagas, 2004). The significance of these seven semantic scales is represented in Table 1.

The decision maker also has the freedom to choose more than one consecutive categories, if the comparison using the provided seven semantic scales is observed to be unreasonable. The judgments provided by the decision maker are checked for consistency.

At this point, it is quite obvious that the level of complexity increases and the efficiency on the method application decreases with the number of criteria. Moreover, the strategy to correctly assign semantic values (ensuring significance) may get quite confusing. The use of M-MACBETH[3] software provides support to its usage, although still requiring some guidance from experts on the method.

To avoid this increase on complexity, while coping with LifeSaver requirements in terms of decision support, authors propose a modification to the MACBETH method relying on the use of direct criteria weighting. This is possible due to the limited number of criteria that are to be considered at LifeSaver as well as to the fact that these criteria are fixed (see the following section for criteria definition). Moreover, since all the parameters that are going to be involved in the decision process are quantifiable, qualitative assessment of alternatives is seen as not essential.

This modification is only possible due to the specific scenario in which we are focusing (industrial energy efficiency). The inputs from industrial partners involved on LifeSaver (established in the form of business case requirements (Marques and Neves-Silva, 2013)) have contributed for the establishment of this approach.

[3] Demo version of the software is available at http://www.m-macbeth.com/.

Table 1
Significance of MACBETH semantic scales.

Semantic scale	Equivalent numerical scale	Significance
Null	0	Indifference between alternatives
Very Weak	1	An alternative is very weakly attractive over another
Weak	2	An alternative is weakly attractive over another
Moderate	3	An alternative is moderately attractive over another
Strong	4	An alternative is strongly attractive over another
Very Strong	5	An alternative is very strongly attractive over another
Extreme	6	An alternative is extremely attractive over another

2.3.2. Main criteria for Process Reconfiguration and ETS

The criteria for energy efficiency and energy management in industry can be either quantitative or qualitative. In what concerns LifeSaver the objective of decision support for process reconfiguration is to understand how to save energy in current operations. In what regards support for ETS the idea is to support companies in taking advantage of the emission trading system. In both cases, the primary purpose of decision support is to validate that time, effort and money invested provides the expected results.

The envisaged results from the end-users point of view can be synthetized as improving production planning and process control system by integrating energy and environmental management.

To cope with this objective a set of criteria were identified as being important for LifeSaver. Table 2 presents the main criteria identified for LifeSaver decision support for Process Reconfiguration and ETS as well as a number of associated sub-criteria. Note that this list is not exhaustive and may be revised during the project. Note also that LifeSaver industry orientation drives into highly concrete and tangible scenarios. This results in having a set of mains criteria and sub-criteria against which alternatives can actually be computed or measured.

2.3.3. Decision algorithm for Process Reconfiguration and ETS

The approach proposed for LifeSaver can be broken down into the following steps.

2.3.3.1. Step 1 – scenario collection. In this step an inventory of the testing scenarios is collected based on the inputs from plant expert users. In what regards Support for Process Reconfiguration and ETS,

Table 2
Main criteria for Process Reconfiguration and ETS and associated sub-criteria.

	Criteria	Sub-criteria	
Criteria Main Categories	Energy Use	EU_1	Energy consumption by time unit
		EU_2	Energy use by process
		EU_3	Energy savings by retrofitting
	Emissions	E_1	Emissions by time unit
		E_2	Emissions reduction potential
		E_3	Environmental impact
	Production	P_1	Production capacity
		P_2	Expected production
		P_3	Utilized capacity
	Cost	C_1	Direct cost and investment
		C_2	Maintenance costs
		C_3	Life span
		C_4	Emission allowance cost
		C_5	Net Present Value (NPV)
		C_6	Internal Rate of Return (IRR)

and in the simplest case, the analysis will be made considering the "AS-IS" situation with one "TO-BE" situsation.

2.3.3.2. Step 2 – definition of criteria. In order to be as exhaustive as possible and to define the question properly, particular attention must be given to the definition of criteria. On the other hand, the number of criteria must not exceed a reasonable limit. The list proposed in previous sections may be used as a starting point and other criteria may be added to it.

2.3.3.3. Step 3 – analysis of the scenarios. Once the scenarios and criteria have been defined, a quantitative estimation must be made. Based on the criteria and scenarios to be evaluated, a multi-criteria evaluation matrix is build. This matrix is a table with as many columns as there are criteria and as many lines as there are scenarios to be compared (see Table 3).

In this table,

$$w = w_{eu} + w_e + w_p + w_c = 1 \tag{12}$$

and the sum of each sub-weighting, associated to each criteria, must also be one.

2.3.3.4. Step 4 – evaluation of scenarios in terms of each of the selected criteria. The scenarios are scored for each criterion. The values obtained by each scenario regarding each criterion are mapped into an interval from [0,1] as follows:

$$V_{S_{sw}} = \frac{\text{ActualValue} - \text{MinimumValue}}{\text{MaximumValue} - \text{MinimumValue}} \tag{13}$$

where

- ActualValue – represents the absolute value of the scenario for that criteria
- MinimumValue – represents the minimum (worst) accepted value for that criteria
- MaximumValue – represents the maximum (best) accepted value for that criteria

This way we will be avoiding regular normalization, which is totally blind to user preferences.

Note that, as explained above, the methodology also accepts qualitative description of the impact of each scenario, in terms of criteria, (e.g. impact descriptors – e.g. neutral, significant, etc.). In these cases an additional mapping between the descriptors and the values is needed. As this case is not foreseen within LifeSaver it is not developed here.

The overall value obtained by each scenario is calculated by:

$$OV_n = \sum_{i=1}^{m} w_i * \left(\sum_{j=1}^{k} sw_j * V_{n_{sw_j}} \right) \tag{14}$$

with: n – the number of scenarios; m – the number of criteria; k – the number of sub-criteria inside each criterion.

The overall values (OV) obtained for each scenario will be between [0,1] with the best scenario being the one presenting higher score i.e. closer to 1.

2.3.3.5. Step 5 – sensitivity analysis. It is also important to understand how variations on parameters or variations on the criteria weights affect the results obtained. Basically this corresponds to applying some sort of sensitivity analysis on the final result, i.e. a "what-if" question to see what happens when some modification is

Table 3
LifeSaver evaluation matrix.

	Criteria	Energy use			Emissions			Production			Cost					
	Weight (w)	w_{eu}			w_e			w_p			w_c					
	Sub-criteria	Energy consumption by time unit	Energy use by process	Energy savings by retrofitting	Emissions by time unit	Emissions reduction potential	Environmental impact	Production capacity	Expected production	Utilized capacity	Direct cost and investment	Maintenance costs	Life span	Emission allowance cost	Net Present Value (NPV)	Internal Rate of Return (IRR)
	Sub-weight (sw)	w_{eu_1}	w_{eu_2}	w_{eu_3}	w_{e_1}	w_{e_2}	w_{e_3}	w_{p_1}	w_{p_2}	w_{p_3}	w_{c_1}	w_{c_2}	w_{c_3}	w_{c_4}	w_{c_5}	w_{c_6}
Scenarios	Scenario 1	$V_{1_{eu_1}}$	$V_{1_{eu_2}}$	$V_{1_{eu_3}}$	$V_{1_{e_1}}$	$V_{1_{e_2}}$	$V_{1_{e_3}}$	$V_{1_{p_1}}$	$V_{1_{p_2}}$	$V_{1_{p_3}}$	$V_{1_{c_1}}$	$V_{1_{c_2}}$	$V_{1_{c_3}}$	$V_{1_{c_4}}$	$V_{1_{c_5}}$	$V_{1_{c_6}}$
	Scenario 2	$V_{2_{eu_1}}$	$V_{2_{eu_2}}$	$V_{2_{eu_3}}$	$V_{2_{e_1}}$	$V_{2_{e_2}}$	$V_{2_{e_3}}$	$V_{2_{p_1}}$	$V_{2_{p_2}}$	$V_{2_{p_3}}$	$V_{2_{c_1}}$	$V_{2_{c_2}}$	$V_{2_{c_3}}$	$V_{2_{c_4}}$	$V_{2_{c_5}}$	$V_{2_{c_6}}$
	…															
	Scenario n	$V_{n_{eu_1}}$	$V_{n_{eu_2}}$	$V_{n_{eu_3}}$	$V_{n_{e_1}}$	$V_{n_{e_2}}$	$V_{n_{e_3}}$	$V_{n_{p_1}}$	$V_{n_{p_2}}$	$V_{n_{p_3}}$	$V_{n_{c_1}}$	$V_{n_{c_2}}$	$V_{n_{c_3}}$	$V_{n_{c_4}}$	$V_{n_{c_5}}$	$V_{n_{c_6}}$

introduced in any of these inputs and to what extent they affect the output. This will contribute for an increased understanding of the relationships between input and output variables in the decision process.

Sensitivity analysis in LifeSaver relies on running the energy models developed, taking into account the level of uncertainty measured in the different parameters of the model, and considering the "what-if" question introduced.

2.3.3.6. Step 6 – store results. In the end of the process, results are stored in such way that enables the identification of the alternative selected. The alternative is selected by the user(s), for this authorised users will have to be identified within each company. Storing the results will enable traceability of the decision process as well as analysis of the outcome of choosing a specific path.

3. Tests and results

3.1. Test case 1: decision support for immediate reaction at cement production

Cement production is one of the most energy intensive processes in industry, causing large amounts of CO_2, dust and other emissions, noise (quarry). According to IEA (2007), global cement industry accounts for about 70%–80% of the energy use in the non-metallic minerals sub-sector, consuming 8.2 exajoules (EJ) of energy a year (7% of total industrial fuel use – year 2005) and accounts for almost 25% of total direct CO_2 emissions in industry. LifeSaver platform is being tested via a prototype information system in the largest cement-producer in Slovenia, Salonit Anhovo (Salonit). Salonit has provided a real testing environment for the validation of the proposed concept of decision support for immediate reaction.

For testing purposes Salonit provided data related to rotary clinker furnace. Note that, since the alternatives provided by Salonit did not include associated costs, the algorithm was tested without that perspective. For the initial testing the data samples were collected on a one minute interval for the period of seven days, which resulted in 10080 samples of each input signal. Testing days were carefully selected assuring that all used fuels were covered, meaning that each individual fuel has been used at least once. Data was collected using the format presented in Table 4, where (PS) represents the production stage, (T) represents the control room team, (X1, X2, X3, X4, X5, X6, X7, X8) represent the energy carriers flow from which fuel mix is derived, and (AS1, AS2) represent auxiliary systems. Table 5.

LifeSaver compares the actual energy consumption data with the predicted values and benchmark values for the team and factory. Also, the system compares the predicted energy consumption data with the benchmark values for the team and factory. In case a deviation is detected (i.e. value higher than the benchmark value for the team and factory) the system generates Event 1 "Deviations on Fuel Mix" and a Decision Process with status "CREATED" is stored at the database.

The Decision Support Services BB initiates the support for Immediate Reaction and finds 50 Decision Processes stored at the database with status "CLOSED". All these Decision Processes are related with situations of abnormal energy consumption. The degree of similarity between cases is established through the Event detected (which congregates the information presented in Table 4) and is computed as follows:

$$\mathrm{Sim}(E_1, E_2) = \sum_{i=1}^{n} w_i e^{-(\gamma|\alpha_{1i}-\alpha_{2i}|)} \tag{15}$$

Table 4
Data collection format for Salonit test scenario.

PS	T	X1	X2	X3	X4	X5	X6	X7	X8	AS1	AS2
ps_a	t_a	x_{1aa}	x_{2aa}	x_{3aa}	x_{4aa}	x_{5aa}	x_{6aa}	x_{7aa}	x_{8aa}	as_{1aa}	as_{2aa}
	t_b	x_{1ab}	x_{2ab}	x_{3ab}	x_{4ab}	x_{5ab}	x_{6ab}	x_{7ab}	x_{8ab}	as_{1ab}	as_{2ab}
	t_c	x_{1ac}	x_{2ac}	x_{3ac}	x_{4ac}	x_{5ac}	x_{6ac}	x_{7ac}	x_{8ac}	as_{1ac}	as_{2ac}
Factory benchmark		x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	as_1	as_2

where α_{1i} and α_{2i} are the parameters of each Event, w_i is the weight of each parameter and γ is a scaling factor. The computation of similarity, and the subsequent selection of cases, is performed using a similarity threshold of 90% (all the cases with similarity level below 90% are discarded). The set of similar cases includes 23 Decision Processes. From these, six are associated to Cause 1 "Problems with fuel sensor" and 17 are associated to Cause 2 "Unbalanced fuel dosing", thus: $p(C_1|E_1) = 0.26$ and $p(C_2|E_1) = 0.74$.

All the cases associated to Cause 1 were solved using Alternative 1 "Reset or Replace sensor", whereas half cases associated to Cause 2 were solved using Alternative 2 "Reduce dose rate of X1, confirm dosing of X2 and check the status of the auxiliary systems" and the other half using Alternative 3 "Confirm dosing of X4, X5, X6 and check the status of the auxiliary systems", thus: $p(A_1|(C_1|E_1)) = 1$, $p(A_2|(C_2|E_1)) = 0.5$ and $p(A_3|(C_2|E_1)) = 0.5$.

The cases were grouped considering the Cause and the Alternative and the mean similarity was computed for each sub-set of cases, resulting in: $\overline{\mathrm{Sim}_1} = 0.9308$, $\overline{\mathrm{Sim}_2} = 0.9180$ and $\overline{\mathrm{Sim}_3} = 0.9702$.

The final score for each is then computed using (1): $\mathrm{Score}_1 = 0.2428$, $\mathrm{Score}_2 = 0.3392$ and $\mathrm{Score}_3 = 0.3585$.

After this process the alternative recommended to the user is Alternative 3 (due to the higher score obtained). Nonetheless, all the alternatives considered are presented to the user. The user selects and implements one of the possible alternatives and closely monitors the clinker burning process. The system stores the user selection and changes the status of the Decision Process from "CREATED" to "SELECTED". In case no new deviations are detected in a specific time frame the user informs the system that Alternative 3 was successful and the status of the Decision Process is changed to "CLOSED". From now on, this Decision Process will be usable in future situations. This action serves to measure the success of the suggestion provided.

3.2. Test case 2: decision support for Process reconfiguration and ETS at paint production

LifeSaver prototype is also being tested at J.W. Ostendorf GmbH & Co. KG (JWO), a large producer and supplier of paints and varnishes. JWO has provided a real testing environment for the validation of the proposed concept of decision support for process reconfiguration and ETS.

For testing purposes JWO provided data related to production of white dispersion paint, which can be produced in 10 different production lines. Each production line is equipped with different dispersers, resulting in varying energy consumption for the production of the same product. Hence the selection of the most energy efficient production line will represent an appropriate means

Table 5
Data collection format for JWO test scenario.

PL	1	2	3	4	5	6	7	8	9	10
Scenario										
Scenario 1	pt_1	pt_2	pt_3	pt_4	pt_5	pt_6	pt_7	pt_8	pt_9	pt_{10}
Scenario 2	pt_2	pt_7	pt_8	pt_{10}	pt_3	pt_5	pt_4	pt_1	pt_9	pt_6
Scenario 3	pt_3	pt_9	pt_7	pt_6	pt_{10}	pt_5	pt_1	pt_8	pt_4	pt_2

to reduce energy consumption in the process. Nonetheless, and due to process restrictions, there are other types of paints that can only be produced in specific lines. Note that, in this test scenario, JWO is not considering Emissions or Costs. In fact the scenarios are scored considering the utilization of the installed capacity, using only electric energy, which will be, in the end, the main selection point.

The testing data included the elaboration of three different scenarios, representing 10 different orders (including white dispersion paint and other 9 types of paint) and aiming at finding the best selection of production lines to produce the orders. The scenarios were elaborated with the support of JWO experts resulting in:

where (PL) represents the production line, and (pt_i) represents the type of paint to be produced (including the viscosity and the recipe, with impact in the energy consumption). The scenarios are simulated using the LifeSaver prediction capabilities and the results are used for scoring. Table 6 presents the options made in terms of criteria weight, acceptable intervals as well as the normalised results obtained for each scenario in each category and the overall score.where:

$$V_i(eu_{1i}) = \frac{eu_{1i} - \min EU_1}{\max EU_1 - \min EU_1}, i = 1, 2, 3$$

$$V_i(eu_{2i}) = \frac{eu_{2i} - \min EU_2}{\max EU_2 - \min EU_2}, i = 1, 2, 3$$

$$V_i(p_{3i}) = \frac{p_{3i} - \min P_3}{\max P_3 - \min P_3}, i = 1,\ 2,\ 3$$

Once the process is completed the system presents the results ranking the scenarios by the score obtained. In this case Scenario 3 is considered the most adequate one, followed by Scenario 2 and, in the last position, Scenario 1. In case the user wants to start a production order this information supports the selection of the most energy efficient production lines combination. The scenarios and related score are stored in the knowledge repository associated to a Decision Process that can, at any time, be accessed. The quality of the result is measured by the feedback of the user in terms of "degree of satisfaction" with the suggestion provided.

4. Discussion

For Test Case 1 the main objective is overall performance improvement by eliminating, or at least reducing, behaviours that lead to increased energy consumption. The proposed approach combined with the new hardware and software and introduction of postulates of energy and environmental management into Salonit's daily activities represents introduction of change in people's attitude about energy use in daily operational practices and routines.

The results of the decision model have confirmed the possibility of using such a model for responding to energy consumption deviations that require an immediate reaction to restore normal situation. Due to availability of the reliable historical/past data the results obtained with the decision model were appropriate for the situations detected and considered excellent.

During the testing phase predicted values of the energy consumption (for each particular fuel and electricity) were compared with the context specific benchmark values (for each team and fuel mix) to facilitate understanding of energy use patterns and trigger early warning and reaction if needed. Initial testing results have confirmed the potential of energy savings enabled by proper and tailor made consumption feedback through decision support services which successfully influenced on the established behavioural patterns of less efficient process operators.

In what concerns Test Case 2 the main objective is to support JWO operators in finding strategies to enhance energy efficiency. The results obtained have confirmed the possibility of the proposed approach to provide information on the best scenario production line selection. During the testing phase predicted values of the energy consumption were compared and information regarding contextual variables was considered (e.g. specific viscosity of the paint). Initial testing results have confirmed the potential of energy savings enabled by suggesting the most energy efficient production line combination for each production order.

In both test cases, limitations of the proposed concept are related with the requirements for expert knowledge during modelling period and definition of the initial set of context sensitive information. Also, context extraction from the available history data requires a significant amount of time, efforts and experience, especially when there is an intention to involve variables that will contextualize complex industrial operations.

Table 6
LifeSaver matrix for JWO test scenario.

Criteria	Energy use		Production	
weight	0.8		0.2	
Sub-criteria	EU_1	EU_2	P_3	
Sub-weight	0.7	0.3	1	
Acceptance interval	[minEU_1; maxEU_1]	[minEU_2; maxEU_2]	[minP_3;maxP_3]	
				OV
Scenario 1	$V_1(eu_{11}) = 0.5$	$V_1(eu_{21}) = 0.6$	$V_1(p_{31}) = 1$	0.624
Scenario 2	$V_2(eu_{12}) = 0.6$	$V_2(eu_{22}) = 0.6$	$V_2(p_{32}) = 1$	0.68
Scenario 3	$V_3(eu_{13}) = 0.5$	$V_3(eu_{23}) = 0.5$	$V_3(p_{33}) = 1$	0.7

5. Conclusions

The work developed and results obtained are adequate for LifeSaver objectives in the field of contextualized decision support. The categorization proposed, in the form of two different decision support strategies, served as base for defining the methods to be applied. The *support for immediate reaction* is based on the paradigm of intelligent decision support implemented through the use of Case-based Reasoning together with probabilistic analysis. *Process reconfiguration and ETS* is implemented through the use of multi-criteria decision analysis based on MACBETH method. The modification proposed on the use of MACBETH is aligned with the specific characteristics of LifeSaver and derives from the requirements provided by industrial end-users. The algorithms for both approaches are proposed, as well as an analysis of the knowledge that needs to be collected to enable the decision. The results being obtained at end-users trials provide a good input for the rest of the development and refinement of the tool.

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