Structured Methodology for Selection of Maintenance Key Performance Indicators: Application to an Oil Refinery Plant

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The novel contribution of the work is the proposal of a structured multi-step methodology that may support the Decision Maker (DM) in the measurement of maintenance performance by means of Maintenance Key Performance Indicators (MKPIs). To this aim, a multi-level hierarchical framework able to synthesize the most meaningful aspects affecting the maintenance results is designed. Then, MKPIs are selected from the literature, assigned to the hierarchical framework and ranked by an Analytic Hierarchy Process-based approach with incomplete comparison matrices. A mathematical model is finally formulated to select the optimal set of MKPIs. The methodology is implemented in an oil refinery plant and entirely designed with the subject company maintenance staff.

Keywords: Maintenance Key Performance Indicators (MKPIs), Hierarchical Framework, AHP, Incomplete Pair-Wise Comparison Matrices, Mathematical Programming, MKPIs Selection

1. Introduction

The International Standard EN 13306 (2010) defines maintenance as "the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function". Nowadays, maintenance is more and more considered as an important support function in business with significant investments in physical assets and plays an important role in achieving the organizational goals (Certa et al., 2012; Certa et al., 2013; Tsang, 2002). In this regard, the International Standard ISO 55000 (2014) includes maintenance among the most relevant asset management subject areas to be effectively managed and controlled to realize value. Actually, maintenance is a multi-disciplinary process whose an effective and efficient management is fundamental to assure an high performance of assets, i.e. high availability, high level of safety and good quality of products (Löfsten, 2000; Swanson, 2001). With this recognition, the measurement of the maintenance performance has become an essential element of the strategic thinking of asset owners and managers for identifying business processes, areas and departments that need to be improved to achieve the organizational goals (Parida, 2006)

So far, a lot of contributions have been proposed in the literature for the assessment of the overall organizational performance, whereas more future systematic research efforts are still needed as regards the area of maintenance performance measurement and management in order to consolidate theoretical constructs and promote the utilization of more practical applications (Simões et al., 2011; Galante et al., 2015). The main literature on Maintenance Performance Measurement (MPM) models and Maintenance Key Performance Indicators (MKPIs) principally has two drawbacks. Firstly, proposed MPM models commonly disregard the business specific environment of the company wherein these tools should be applied, namely MPM frameworks are not customized on the basis of the industrial context under investigation. Then, MKPIs suggested by the technical and scientific literature are numerous but an agreed-upon methodological approach for selecting the best suitable/useful ones depending on the specific context still lacks. With these recognitions, the novel contribution of the work is the proposal of a structured, multi-step and customized MPM methodology based on the use of a restricted and comprehensive list of MKPIs. The industrial context which the developed methodology is based on is that of an oil refinery plant where the way maintenance process is managed and implemented surely takes a crucial role in the prevention of hazardous events' occurrence (Curcurù et al., 2012; Curcurù et al., 2013; Carpitella et al., 2016; Certa et al., 2017). Since the necessity of the maintenance manager to measure, monitor and communicate the maintenance process results to both the board and the maintenance technicians as regards different perspectives, the subject company maintenance staff has been actively involved in the design and implementation of the whole methodology. The latter comprises the following steps. Aiming at capturing the most fundamental aspects (i.e. perspectives) affecting the effectiveness and the efficiency of the maintenance process of the oil refinery, a customized hierarchical structure is firstly designed. In particular, the hierarchical structure is addressed to the company's maintenance manager because of his/her needs to synthesize the maintenance process results to the top management and to detail them to the maintenance technicians. Therefore, the hierarchical framework is developed so as to highlight all those maintenance aspects that the maintenance manager deems to be crucial to vertically communicate the maintenance performance and eventually to improve it. The hierarchical structure comprises more than one level so that information returned by each level provide a greater detail on a particular aspect of the immediately higher one. Successively, on the basis of a detailed review of the main technical and scientific literature on MKPIs, indicators deemed to be the most appropriate to describe the specific maintenance process are selected as well as several indicators are ad-hoc formulated by the involved maintenance staff to detail the returned information. Collected MKPIs are then assigned to each lowest level aspect of the hierarchical framework. Aiming at prioritizing the assigned MKPIs, an Analytic Hierarchy Process (AHP)-based approach (Saaty, 1994) is successively proposed. Differently from the traditional AHP applications, incomplete pair-wise comparison matrices are here supposed to be elicited from the decision maker (i.e. the maintenance manager) that is actually asked to provide just those pair-wise comparison judgments on which he/she is confident. The Revised Geometric Mean (RGM) method, or incomplete pair-wise comparison algorithm of Harker (1987), is then used to complete pair-wise comparison matrices. Obviously, dealing with a huge number of MKPIs can be counterproductive for a twofold reason. Firstly, managing too many indicators leads to the lack of conciseness of the returned information. Then, the computational effort becomes considerable in terms of amount and type of input data to be recorded. Therefore, among all those assigned, a restricted and comprehensive number of MKPIs has to be selected to synthetically measure and communicate the maintenance process performance. To this aim, a mathematical programming model is formulated. In particular, the optimal set of MKPIs is asked to be the best compromise between the information completeness (i.e. covering all the most meaningful aspects of the maintenance process) and the computational effort required (i.e. amount and type of input data to be recorded).

To the authors' opinion, the proposed approach can be applied to other industrial contexts even if it is specifically designed with reference to an oil refinery plant. Actually, the main purpose of the present paper is to fill a gap in the literature of a structured approach able to support maintenance managers during the decision-making process addressed to the measurement of maintenance performance by the identification of a reduced list of MKPIs. The way the methodology is designed forces the maintenance manager to a more detailed analysis of the decisional problem and facilitates the selection of the most suitable MKPIs to synthetically describe those perspectives that more meaningfully affect the maintenance results. Nevertheless, one has to bear in mind that each organization is unique in its structure, function and business position, so that the hierarchical framework used to capture all maintenance critical aspects needs to be customized with relation to the specific organizational context.

The remainder of the paper is organized as follows. The literature review is supplied in Section 2 whereas the whole methodology is synthesized in Section 3 together with a detailed explanation of the first steps of the methodology itself. Section 4 presents a brief overview on the traditional AHP method and the designed AHP-based approach with incomplete pair-wise matrices addressed to the MPM. Next Section 5 reports the mathematical programming model formulated to identify the optimal set of MKPIs. The industrial case is reported in Section 6 whereas Conclusions are finally drawn in Section 7.

2. Literature Review

The most widely used business performance model is the Balanced Scorecard (BSC) of Kaplan and Norton (Kaplan and Norton, 1996). The BSC is a holistic approach that transfers the strategy into clearly defined goals related to four different perspectives, namely financial, customer, internal processes and learning and growth. Then, for each of such a perspective, indicators, target values and activities needed to achieve the goals are defined. The standard BSC model has been also used for the MPM (Tsang, 1998; Visser and Pretorius, 2003) but the feasibility of applying the BSC for managing the performance of a specific function such as maintenance is still an uncharted area which needs researching (Tsang et al., 1999). In fact, the traditional four perspectives of the BSC model are not able to capture all facets of the maintenance function because of the several interrelationships between maintenance and the other organizational functions. As a consequence, several literature contributions try to adjust the BSC to the MPM problem by adding further perspectives (Alsyouf, 2006; Bakhtiar et al., 2009; Mather, 2005; VDI 2893, 2006; Wireman, 1998). Despite the wide use of BSC and of its enhanced versions to the MPM problem, to the authors' opinion it is not easily understandable by the maintenance staff (i.e. managers and technicians). Furthermore, each organization is unique in its structure, function and business position so that a performance measurement framework may be suitable for one organization and may not be for another one (Parida, 2006). Therefore, a MPM model should be focused on the specific organizational context with the aim of identifying the critical (key) factors influencing the overall maintenance effectiveness and efficiency.

So far, the overall organizational performance has been commonly measured by means of KPIs. In this regard, several contributions deal with the setup and prioritization of KPIs generally arising from the existing literature especially as concerns the Health, Safety and Environmental (HSE) field (Savino and Apolloni, 2007; Lee et al., 2008; Wua et al., 2009; Ramon et al., 2010; Jalilova et al., 2012; Lin et al., 2012; Sadoughi et al., 2012). Referring to the maintenance function, several related issues (i.e. choice of the maintenance policy, scheduling of maintenance actions, selection of outsourcing contractors, etc..) have been widely researched in the literature, and Multi-Criteria Decision Making (MCDM) methods have been extensively used as support tools to deal with such kinds of decisional problems. For instance, Kim and Meoli (2012) develop a failure-based plant maintenance management approach and the related ERP application by means of which facilitating a fast localization of spare parts. De Felice et al. (2010) firstly analyze the principal techniques of reliability allocation and then propose a new reliability allocation method which determines the reliable criticalities of a production system. Rienkhemaniyom and Ravi Ravindran (2016) assess the vulnerability of a supply chain network by a mixed integer linear programming approach and analyze the effectiveness of risk mitigation strategies. Braglia et al. (2006) suggest an AHP-based methodology to select the best suited Computer Managed Maintenance System (CMMS) software within process industries. Multiple and often conflicting evaluation criteria are considered, and a sensitivity analysis is performed to improve the effectiveness of the methodology. AHP is one more time proposed by Bertolini et al. (2004) to select the best alternative among different outsourcing contracts in terms of maintenance services. Taking into account the budget and the amount of hours of manpower labour as constraints, Bertolini and Bevilacqua (2006) present a combined goal programming and AHP based approach to select the best maintenance strategy among corrective, preventive and predictive ones for the centrifugal pumps of an oil refinery plant. Also Arunraj and Maiti (2010), propose goal programming together with AHP to deal with the maintenance strategy selection considering the risk of equipment failure and the cost of maintenance as evaluation criteria. Savino et al. (2015) implement a fuzzy AHP approach within a Failure Mode and Effects Analysis (FMEA) to investigate on how human rights issues, labor standards and safety standards are considered to drive the prioritization of maintenance interventions. In (Vishnu and Regikumar, 2016) AHP is proposed to deal with the selection of the reliability centered maintenance strategy in process plants.

As regards MKPIs, those proposed by the scientific and technical literature are numerous principally with relation to the discrete parts manufacturing sector (EN 15341, 2007; Neubert et al., 2010; Savino et al., 2011; SMRP Press Release, 2007; Weber and Thomas, 2006) but only few contributions address to the MKPIs' selection problem. Amodeo (2005) starts from the BSC concept to define the fundamental aspects (pillars) upon which the overall maintenance operation rests. From these basic pillars, a hierarchical decomposition is proposed to identify the lowest measurable functions whereby obtaining the fundamental attributes to be used to manage the general goal. Muchiri et al. (2010) refer to Belgian industries to determine which are the most commonly used MKPIs, how they are chosen and how they can be effectively used in decision support and performance improvement. A conceptual framework that provides a guideline for choosing maintenance performance indicators, through alignment of manufacturing objectives and maintenance objectives, is developed by Muchiri et al. (2011). Authors emphasize that further research work is recommended on the methodological approach of choosing the right MKPIs among the given indicators listed in the literature. Van Horenbeek and Pintelon (2014) develop a generic hierarchical framework which is based on the corporate and maintenance strategy and incorporates all organizational levels (i.e. strategic, tactical and operational). Then, authors suggest an Analytic Network Process (ANP)-based method to customize the proposed framework. In (Gonçalves et al., 2014), the ELimination ET Choix Traduisant la REalité (ELECTRE) I method (Roy, 1968) is introduced for the MKPIs ranking on the basis of five different evaluation criteria. Then, MKPIs ranked at the first eight positions are selected by the analyst without the application of any structured approach.

3. Multi-Step Methodology for the Measurement of the Maintenance Process Performance

The multi-step methodology here proposed to measure the performance of the maintenance process by means of a restricted number of MKPIs is organized as follows.

1. **Step 1:** definition of a customized hierarchical framework able to synthesize all those aspects that affect the maintenance performance of the specific organization.
2. **Step 2:** collection of MKPIs proposed by the scientific and technical literature, and selection among those collected of MKPIs deemed to be the most appropriate to be used in the particular organizational context. Definition of further specific indicators if necessary.
3. **Step 3:** assignment of selected MKPIs to the lowest level aspects of the hierarchical framework.
4. **Step 4:** application of the AHP-based approach to prioritize the assigned MKPIs.
5. **Step 5:** formulation of a mathematical programming model addressed to the identification, among those assigned, of the optimal set of MKPIs that represents the best compromise between the completeness of the returned information and the required computational effort in terms of amount and type of input data to be recorded.

The whole methodology and phases it comprises are detailed in the next sections.

3.1 Step 1: Definition of the Customized Hierarchical Framework

Aiming at capturing the most fundamental aspects affecting the effectiveness and the efficiency of the maintenance process managed and performed within the specific organizational context, a customized hierarchical structure is firstly designed. In particular, the stakeholder whom such a structure is addressed to is the maintenance manager that needs to share the maintenance results with both the company's top management and the maintenance technicians. To this purpose, all maintenance aspects on which paying attention to improve the overall maintenance performance are firstly identified in cooperation with the subject company maintenance staff and then synthesized within the multi-level hierarchical framework shown in Figure 1. Different nodes are associated with each level. In particular, each node is representative of a specific perspective on the basis of which measuring the maintenance performance and, whenever deemed to be necessary, it is further branched in order to detail the considered perspective. The way the hierarchical structure is designed assures that the highest level nodes refer to more generic information potentially interesting for the company's top management. To the contrary, the lowest level nodes are more detailed so that they are mainly addressed to maintenance technicians. A more exhaustive explanation of the proposed hierarchical framework is reported in the following.

The level zero is the goal, namely the measurement of the maintenance process performance. The next level 1 takes into account the most critical perspectives for the maintenance effectiveness and efficiency. Specifically, the following five perspectives are assigned to the level-1 nodes:

- Technical (node 1). It concerns the effectiveness of maintenance actions, namely it aims at highlighting the influence on plant reliability and availability of how maintenance actions are performed within the organization.
- Economical (node 2). It refers to economical aspects of maintenance (maintenance efficiency), from the budgeting to the expenditure phase.
- Organizational (node 3). It regards the way maintenance activities are planned, scheduled and carried out. In addition, it includes all those issues related to the management and training of maintenance personnel.
- Health, Safety and Environment (HSE) (node 4). It highlights the impact of maintenance actions on the health and safety of inner and outer maintenance personnel, as well as on the environment.
- Warehousing (node 5). It aims at describing the efficacy and the efficiency of the maintenance spare parts management.

Successively, each level-1 node is further branched in order to detail the expected information. Referring to the Technical node (node 1), it is branched into the Reliability (node 1.1) and the Availability (node 1.2) nodes. Actually, reliability and availability are two different and common measures of the maintenance process effectiveness. The node Availability (node 1.2) is further branched into the nodes Corrective Maintenance (node 1.2.1), Preventive Maintenance (node 1.2.2) and General (node 1.2.3). Namely, the attention is firstly focused on the two main maintenance policies performed in the plant in order to detail how the way they are carried out affects the plant's availability. Then, the node General aims at describing some general aspects of the plant's availability disregarding the type of maintenance policy.

The Economical node (node 2) is branched into the Corrective Maintenance (node 2.1), Preventive Maintenance (node 2.2) and General (node 2.3) nodes. Nodes 2.1 and 2.2 refer to the efficiency of corrective and preventive maintenance actions, whereas the node 2.3 returns information on the whole maintenance process efficiency disregarding the type of maintenance policy.

Aiming at highlighting if maintenance works are opportunely planned, scheduled and carried out on-time, the Organizational node (node 3) firstly includes an aspect (node 3.1) related to the maintenance actions planning, scheduling and execution. Secondly, the node Personnel (node 3.2) relates to what the organization makes for the maintenance personnel improvement by the training activities.

The HSE node (node 4) involves an aspect related to the safety of inner and outer maintenance personnel (node 4.1), and a further node (node 4.2) that focuses the attention on the environmental impact of the maintenance process. In addition, taking into account the particular organizational context, two further aspects are detailed. The first one (node 4.3) concerns failures due to a wrong maintenance on safety barriers (Francese et al., 2015) installed to prevent the occurrence of hazardous situations or to mitigate the related consequences. The second one (node 4.4) aims at highlighting the right execution of inspection activities on such safety barriers.

Finally, the node Warehousing (node 5) concerns the management of maintenance spare parts both on the effectiveness and efficiency point of views.

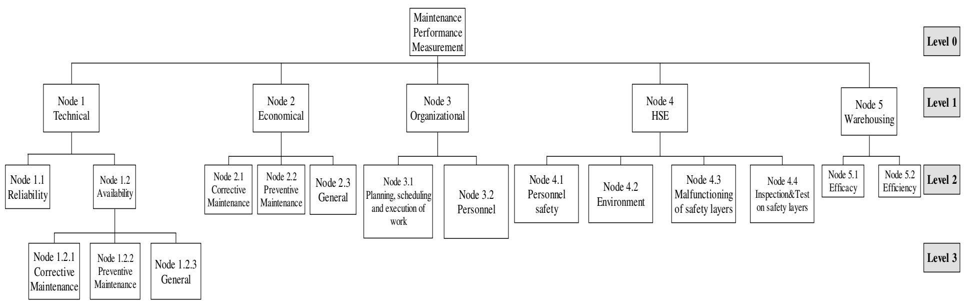

Figure 1 *Customized Hierarchical Framework*

3.2 Steps 2 and 3: Collection and Assignment of MKPIs

Once the hierarchical framework is designed, the next step of the proposed structured methodology concerns the collection and assignment of MKPIs. Actually, indicators are commonly used to measure the overall organizational performance because of their conciseness and easiness of comparison over the time and in respect to other organizations of the same sector. Obviously, a specific function such as maintenance requires specific indicators to measure its performance. As aforementioned, a huge number of MKPIs have been proposed by the technical and scientific literature, but the main part of them refers to the discrete parts manufacturing industry. As a consequence, considering that the industrial context which the present paper is focused on is that of a high risk process plant, MKPIs already proposed in the literature have been collected, reviewed and analyzed in cooperation with the subject company maintenance staff. Therefore, the significance of each MKPI has been evaluated in terms of its applicability to the particular organizational context as well as in terms of its easiness of comprehension and importance to describe a specific maintenance aspect. Among those collected, just those indicators deemed to be useful to describe the specific maintenance process have been selected and then opportunely assigned to the lowest level nodes of the hierarchical structure. In addition, several specific indicators have been formulated by the involved maintenance staff and opportunely assigned to nodes in order to detail the returned information.

Aiming at prioritizing the assigned MKPIs, an AHP-based approach with incomplete pair-wise comparison matrices is proposed and detailed in Section 4, after a brief overview on the traditional AHP method.

4. Step 4: MKPIs Ranking by An AHP-Based Approach with Incomplete Pair-Wise Comparison Matrices

4.1 Overview on the Traditional AHP

The AHP is a widely used MCDM method to support the Decision Maker (DM) in the evaluation and selection of alternatives through the use of pair-wise comparison judgments. AHP starts with the decomposition and hierarchical representation of the decisional problem by the identification of goal, evaluation criteria/sub-criteria and alternatives to be compared. Then, the DM expresses a pair-wise comparison judgment between each pair of items (i.e. criteria, sub-criteria or alternatives) belonging to the same hierarchical level in respect to the immediately higher element. Evaluations are expressed through the use of appropriate semantic scales among which the most used one is the 9-point scale suggested by Saaty (2008) (Table 1).

Table 1 *Saaty's Scale*

Description	Definition	Intensity of importance
Equal importance	The two items are equally important	1
Moderate importance	Experience and judgment slightly favour one item over another	3
Strong importance	Experience and judgment strongly favour one item over another	5
Very strong or demonstrated importance	An item is favoured very strongly over another; its dominance is demonstrated in practice	7
Absolute importance	The evidence favouring one item over another is of the highest possible order of affirmation	9
Intermediate	When compromise is needed, values between two adjacent judgments are used	2, 4, 6, 8

If n is the number of items to be compared with relation to a specific element of the immediately higher level, the total number of judgments elicited from the DM is $[n\cdot (n\text{-}1)/2]$. Each pair-wise comparison judgment constitutes the element a_{ij} of the so-called reciprocal pair-wise comparison matrix $\boldsymbol{A}$. On the basis of collected pair-wise comparison judgments, the local priority (i.e. weight or relative importance) of each element of the hierarchical structure in respect to the immediately higher hierarchical level is computed by means of a method of those proposed in the literature. Among them, the most used one is the eigenvector method (Saaty, 2003).

However, local priorities make sense only if arising from consistent or near consistent matrices. As a consequence, a consistency check on opinions expressed by the DM needs to be performed by the computation of the Consistency Index (CI) and of the Consistency Ratio (CR) proposed by Saaty (1977). In general, a CR of 0.10 or less is considered as acceptable, namely input judgments are considered acceptably inconsistent, hence reliable. Otherwise, the DM is commonly asked to provide again his/her own judgments until an acceptably inconsistent pair-wise matrix is obtained. Finally, local priorities are synthesized across all criteria in order to determine the global priority of alternatives in respect to the goal. In this regard, the distributive or the ideal methods may be used (Belton and Gear, 1983; Saaty and Vargas, 1993; Saaty and Vargas, 2012).

4.2 Eliciting Pair-Wise Comparison Judgments from the DM

An AHP-based method is here used to derive the relative importance of all nodes and of MKPIs assigned to the lowest level nodes of the hierarchical framework. Referring to the specific organizational context, the goal is the MPM whereas alternatives to be evaluated and ranked are the assigned MKPIs. However, a clarification is needed for a better understanding of the AHP application to the particular case. Commonly, the AHP hierarchical structure includes criteria and sub-criteria on the basis of which ranking the available alternatives. Instead, the here proposed hierarchical framework comprises those aspects on the basis of which evaluating the maintenance process performance. The AHP can be used to determine their relative importance in respect to the immediately above hierarchical level. For instance, let suppose to compare the Technical aspect (i.e. Node 1) with the Economical one (i.e. Node 2) in respect to the immediately higher level, namely the goal. Then, expressing a pair-wise comparison judgment means answering the question "*how much more or less important the Technical aspect is than the Economical one of the same level in measuring the maintenance performance?*"

In the traditional AHP method, all alternatives are generally evaluated on all criteria/sub-criteria. Referring to the specific application, alternatives to be compared are the MKPIs assigned to the lowest level nodes of the hierarchical framework. Then, for each node, the assigned alternatives are pair-wise compared on the basis of their ability to describe the aspect they belong to. For instance, let KPI_1 and KPI_2 be two indicators assigned to a generic lowest level node. Then, expressing a pair-wise comparison between the KPI_1 and the KPI_2 means answering the question "*how much do you believe the KPI_1 better or worse describes the aspect represented by the considered node than the KPI_2*?" or also "*how much do you believe the KPI_1 is more or less important than the KPI_2 to describe the aspect represented by the considered node*?". As example, Table 2 shows the pair-wise comparison matrix related to the *m* KPIs assigned to the generic node *k* of the hierarchical structure.

Table 2 *Example of Pair-Wise Comparison Matrix between KPIs Assigned to the Generic Node K of the Hierarchical Structure*

Node *k*	**KPI_1**	**KPI_2**	**…**	**KPI_m**
KPI_1	1	…	…	…
KPI_2		1	…	…
…			1	…
KPI_m				1

However, the DM might not have a strong opinion on a comparison judgment so that he/she is not able to express any evaluation. That is particularly true with relation to pair-wise comparison judgments concerning MKPIs because of a real difficulty of the DM to fully appreciate their different descriptive ability. In such a situation, one could alternatively proceed as follows:

1. Forcing the DM to express all pair-wise comparisons required by the AHP method (see Section 4.1).
2. Allowing the DM to express only pair-wise comparisons on which he/she is confident and eventually force him/her so that judgments span all elements of the pair-wise comparison matrix.

To the authors' opinion, referring to pair-wise comparison judgments among MKPIs, the best way to proceed is that described at the point 2, namely allowing the DM to provide from $(n\text{-}1)$ to $[n\cdot(n\text{-}1)/2]$ judgments that span all elements of the pair-wise comparison matrix. Whether a pair-wise comparison matrix includes less than $[n\cdot(n\text{-}1)/2]$ comparison judgments as here allowed, such a kind of matrix is commonly defined as incomplete. Therefore, missing judgments need to be determined in order to continue with the application of the AHP. Several approaches have been proposed in the literature to deal with incomplete pair-wise comparison matrices (Carmone et al., 1997; Fedrizzi and Giove, 2007; Gomez-Ruiz et al., 2010). Such methods determine missing values in such a way that the matrix inconsistency is minimized. Among them, the most mentioned and applied completion method is the Revised Geometric Mean or Incomplete Pairwise Comparison algorithm of Harker (1987) synthesized in the following Section 4.3.

As regards the pair-wise comparisons between aspects needed to compute their relative weights, one believes that the problem of the matrix incompleteness cannot occur. As a consequence, all pair-wise comparison matrices concerning the relative importance of each aspect of level i in respect to the aspect of level $(i\text{-}1)$ are here assumed to be complete.

4.3 Revised Geometric Mean (RGM) Method and Consistency Check

Let the DM provide the following incomplete pair-wise comparison matrix $\boldsymbol{C}$, which the generic element is C_{ij}. The missing comparison judgment is C_{13} and, as a consequence, its reciprocal c_{31}.

$$\boldsymbol{C} = \begin{bmatrix} 1 & 2 & - \\ 1/2 & 1 & 2 \\ - & 1/2 & 1 \end{bmatrix}$$

Harker states that computing the principal eigenvector $\boldsymbol{W}$ of the matrix $\boldsymbol{C}$ coincides with solving the same problem with relation to the quasi-reciprocal matrix $\boldsymbol{A}$ which the generic element a_{ij} is obtained as follows (equations 1)

$$a_{ij} = \begin{cases} 0 & \text{if } c_{ij} \text{ is a missing judgment}, i \neq j \\ c_{ij} & \text{if } c_{ij} \text{ is not a missing judgment}, i \neq j \\ 1 + m_i & \text{if } i = j \end{cases} \tag{1}$$

m_i is the number of unanswered questions (i.e. missing judgments) in the row i of the incomplete matrix $\boldsymbol{C}$. Completing $\boldsymbol{C}$ as suggested by Harker, the following matrix $\boldsymbol{A}$ is obtained.

$$\mathbf{A} = \begin{bmatrix} 2 & 2 & 0 \\ 1/2 & 1 & 2 \\ 0 & 1/2 & 2 \end{bmatrix}$$

Therefore, $\boldsymbol{C}$ and $\boldsymbol{A}$ have the same eigenvector $\boldsymbol{W}$ so that the problem of computing $\boldsymbol{W}$ for the matrix $\boldsymbol{C}$ which contains the functional relations becomes that of computing $\boldsymbol{W}$ for the non-negative, quasi-reciprocal matrix $\boldsymbol{A}$. The relation $\boldsymbol{A} \cdot \boldsymbol{W} = \boldsymbol{C} \cdot \boldsymbol{W}$ holds.

Once the DM' pair-wise comparisons are collected, all incomplete matrices are here completed by the Harker' method. Then, our methodology continues with the measurement of the inconsistency of all complete (or completed by Harker) matrices, namely the consistency check described in Section 4.1 needs to be performed. In this regard, one must bear in mind that the Random Index (RI) needed to compute the CR of an incomplete pair-wise comparison matrix is different from that used for a complete matrix of the same size. In (Forman, 1990), the author reports the average value of the RI of matrices of different sizes with a variable number of missing judgments.

Therefore:

1. If the checked matrix is acceptably inconsistent (i.e. CR smaller/equal than/to 0.1), then it is possible to proceed with the computation of local priorities of aspects and MKPIs by means of the eigenvector method.
2. If the checked matrix is unacceptably inconsistent (i.e. CR greater than 0.1), then such an inconsistency needs to be reduced. As mentioned in Section 4.1, the common way to proceed is to force the DM to provide again his/her judgments and to recalculate the CR of the new pair-wise comparison matrix, namely performing again the consistency check. The procedure is reiterated until an acceptable inconsistency is reached. Alternatively, different methods have been proposed in the literature to reduce the matrix inconsistency. The procedure here used is detailed in the following Section 4.4.

4.4 Consistency Improvement of Complete Matrices

Techniques proposed in the literature to improve the matrix consistency (Obata et al., 1999; Saaty 2003; Hu and Tsai, 2006) firstly identify the comparison judgment that results in a greater inconsistency and then suggest a value to replace it. When a change is made, the CR is calculated again and the process is repeated until an acceptable CR is obtained.

The method here used to improve the pair-wise comparison matrix consistency is that suggested by Saaty (2003). It uses the following equation: (2)

$$n \cdot \lambda_{max} - n = \sum_{\substack{i,j=1 \\ i \neq j}}^{n} (\varepsilon_{ij} + \varepsilon_{ij}^{-1}) \qquad (2)$$

Where λ_{max} is the maximum eigenvalue of the matrix $\boldsymbol{A}= [a_{ij}]$ and ε_{ij} is a generic element of the matrix $\boldsymbol{E}$ determined by the Hadamard product (3)

$$\mathbf{A} = \mathbf{W} \cdot \mathbf{E} \tag{3}$$

Being $\boldsymbol{W}= [w_i/w_j]$ the matrix of local priorities of the unacceptable inconsistent matrix $\boldsymbol{A}$. Therefore, the matrix $\boldsymbol{E}= [\varepsilon_{ij}]$ is obtained as follows (equation 4).

$$\mathbf{E} = \mathbf{W}^{-1}\mathbf{A} \tag{4}$$

Namely, each element ε_{ij} of $\boldsymbol{E}$ is calculated by the equation (5)

$$\varepsilon_{ij} = {w_j}/{w_i} \cdot a_{ij} \tag{5}$$

The ε_{ij} farthest from one implies the greatest inconsistency arising from a_{ij}. Then, the corresponding a_{ij} and a_{ji} are deleted from the matrix $\boldsymbol{A}$ that is completed by the Harker' method. The new eigenvector is calculated and the previous a_{ij} is replaced by the Saaty' scale value nearest to the w_i/w_j obtained by the new eigenvector.

Therefore, if the DM is not able to express all judgments, the procedure here proposed preliminary utilizes the Harker' method to complete the pair-wise comparison matrix. Then, aiming at reducing the matrix inconsistency if necessary, the aforementioned ε-method is employed to identify the most inconsistent judgment. In order to replace it, the DM is one more time involved to reformulate such a judgment provided that it was originally supplied by the DM. To the contrary, namely the judgment found to be the most inconsistent one was not previously expressed by the DM, then it means that it arises from the application of the Harker' method. Therefore, at the first iteration of the procedure, it cannot be the most inconsistent one. Instead, during next iterations, even a judgment obtained by Harker could be the most inconsistent one. In such a case, it is erased and the Harker's method applied again. The same procedure is used when the most inconsistent judgment coincides with one of those already reformulated by the DM. The described methodology is reiterated until an acceptable matrix inconsistency is reached.

Summing up, the proposed procedure tries to reduce the matrix inconsistency by involving again the DM just on that judgment he/she was previously able to express if it results to be the most inconsistent one. However, even if reformulated, such a judgment could successively result to be the most inconsistent one so that it is erased and the matrix completed by the Harker' method one more time. For the sake of clarity, the flow-chart of the whole methodology is synthesized in Figure 2.

Once all pair-wise comparison matrices related to aspects and MKPIs are acceptably inconsistent, local priority vectors can be calculated. The final step of the AHP-based approach is the computation of the MKPIs global priority vector in respect to the goal. In this regard, the ideal method is applied. In the present context, the ideal mode is preferred to the distributive one because it avoids that the best MKPI belonging to a more numerous group is disadvantaged in respect to that assigned to a smaller group. Actually, referring to a generic node of the hierarchical framework, using the distributive mode leads to divide the corresponding weight to MKPIs assigned to it. Therefore, the more MKPIs assigned to the node, the smaller the local priority of each MKPI. However, applying the ideal method leads to global priorities that do not sum to one. As a consequence, if deemed to be necessary, one can renormalize by using a normalization method among those already proposed in the literature.

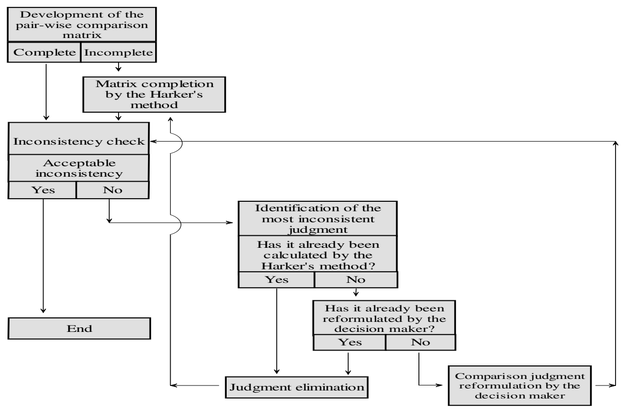

Figure 2 *Iterative Procedure for the Improvement of Pair-Wise Comparison Matrices' Inconsistency*

5. Step 5: Mathematical Programming Model for the Selection of the Optimal Set of MKPIs

Once global priorities of MKPIs in respect to the goal are calculated, the problem of choosing the optimal set of MKPIs still holds. Actually, dealing with a great number of indicators could be troublesome or even counterproductive. Calculating and monitoring over the time numerous MKPIs could result expensive and time-consuming. In addition, it could lead to a *surplus* of information than that effectively needed to check the overall maintenance performance, as well as to a greater difficulty in communicating the maintenance process results to stakeholders. As a consequence, the optimal set of MKPIs needs to be selected among all those previously assigned to the hierarchical framework and ranked by the AHP-based method. Such a set is asked to be the best compromise between the information completeness and the computational effort required to record the needed input data.

Therefore, a mathematical programming model is formulated to identify the optimal set of MKPIs. The used nomenclature is reported below.

- i generic indicator of the list of MKPIs, with $i=1,\ldots,N$.
- j generic node of the level 1 of the hierarchical framework, with $j=1,\ldots,M$.
- g_i global priority of MKPI i arising from the application of the AHP-based method.
- p_j local priority of the node j belonging to the level 1 of the hierarchical framework and calculated by the AHP.

- d_i input parameter representing the computational effort (i.e. difficulty) required to compute the MKPI *i*. In particular, d_i may take a value equal to 0, 0.5 or 1 that stands for low, medium or high difficulty respectively.
- R_{ij} input parameter representing the correlation between MKPIs *i* and *j*. Specifically, such a correlation refers to the necessity of recording common input data to compute both indicators. Therefore, R_{ij} takes a value equal to 0 whether no correlation between *i* and *j* exists, and 1 otherwise.
- n_{min} minimum number of MKPIs to be selected for each node of level 1.
- α_{ij} numerical value that takes 1 if the MKPI *i* belongs to the node *j*, 0 otherwise.
- x_i Boolean variable that takes 1 if the MKPI *i* is selected, 0 otherwise.

The problem is formulated as follows.

$$max \left[k_1 \cdot \sum_{i=1}^{N} x_i \cdot g_i - k_2 \cdot \frac{\sum_{i=1}^{N} \frac{x_i \cdot d_i}{1 + \sum_{j=i+1}^{N} R_{ij} \cdot x_j}}{\sum_{i=1}^{N} \frac{d_i}{1 + \sum_{j=i+1}^{N} R_{ij}}} \right] \tag{6}$$

Subject to

$$(1 - p_j) \cdot \sum_{i=1}^{N} x_i \cdot \alpha_{ij} \geq n_{min} \qquad \forall j \tag{7}$$

$$k_1 + k_2 = 1 \tag{8}$$

The first term of the objective function (6) aims at forcing the model to choose those MKPIs that assure the greatest descriptive ability in accord to the second term that represents the computational effort (i.e. amount and type of data to be recorded) required by MKPIs. Such a second term has to be minimized so that, together with the first objective, leads to select MKPIs that assure the best compromise between the descriptive ability and the computational effort. Both terms of expression (6) range from 0 to 1. The parameters k_1 and k_2 are the weights representing the relative importance that the DM attributes to the two aspects of the problem. For each node of level 1, constraint (7) forces the model to choose at least a fixed number of MKPIs. In particular, it assures the selection of a greater number of indicators from those aspects characterized by a higher weight p_i.

6. Industrial Case

The proposed methodology was implemented in an oil refinery plant located in the South of Italy with the aim of measuring and highlighting the maintenance process results. The oil refinery spreads over an area of 5 million of square meters. Besides the production of crude oil derivatives, it supplies several auxiliary services (thermoelectric unit for the production of electricity and steam, air separation unit for the production of oxygen and nitrogen, water treatment, etc..) indispensable for the operation of the whole plant.

The oil refinery maintenance staff was actively involved for the customization of the hierarchical framework, for the selection of the most meaningful MKPIs among those already proposed in the literature and for the formulation of *ad hoc* indicators deemed to be useful in the specific plant. A total number of 116 MKPIs were collected from the existing scientific and technical literature, whereas 14 were opportunely formulated by the involved maintenance staff. Among those collected from the literature, 44 MKPIs were selected on the basis of their significance and applicability to the specific organizational context. Therefore, 58 MKPIs were totally assigned to the lowest level nodes of the hierarchical framework. Specifically, 14, 17, 9, 13 and 5 MKPIs were assigned to the lowest level nodes belonging to Nodes 1, 2, 3, 4 and 5 respectively. For the sake of privacy of the involved organization, Table 3 synthesizes just few of selected MKPIs and nodes they were assigned to.

Table 3 *Reduced list of MKPIs Assigned to Nodes of the Hierarchical Framework*

Tag	Assigned MKPIs
Node 1.1	Number of plant's shutdowns due to failures/Time horizon
Node 1.2.1	Total operating time/(Total operating time + Downtime due to corrective maintenance); Total operating time/(Total operating time + Downtime related to failures)
Node 1.2.2	Total operating time/(Total operating time + Downtime due to preventive maintenance); Preventive maintenance time causing downtime/Total downtime related to maintenance
Node 1.2.3	Total operating time/(Total operating time + Downtime due to maintenance)
Node 2.1	Corrective maintenance cost/Total maintenance cost; Actual cost of corrective maintenance/Budget cost of corrective maintenance
Node 2.2	Preventive maintenance cost/Total maintenance cost; Actual cost of preventive maintenance/Budget cost of preventive maintenance
Node 2.3	Total maintenance cost/Assets replacement value; Total external personnel cost spent in maintenance/Total maintenance cost
Node 3.1	Number of maintenance actions performed as scheduled/Total number of scheduled maintenance actions
Node 3.2	Total cost of maintenance internal personnel training/Total number of maintenance internal employees; Number of maintenance internal personnel man-hours for training/Total maintenance man-hours
Node 4.1	Number of injuries of personnel/Working time; Number of working days lost for injuries/Working time
Node 4.2	Number of failures due to maintenance creating environmental damage/Calendar time; Annual volume of wastes related to maintenance/Calendar time
Node 4.3	Number of spurious trips of a SIS
Node 4.4	Number of performed tests on safety loops/Number of planned tests on safety loops
Node 5.1	Stock-out; Number of spare parts supplied by the warehouse as requested/Total number of spare parts required by maintenance
Node 5.2	Total cost of maintenance materials/Average inventory value of maintenance materials; Average inventory value of maintenance materials/Asset replacement value

As regards the pair-wise comparison judgments on aspects and MKPIs needed by the AHP-based approach as well as the relative importance weights of the two terms of the objective function, they were expressed by the maintenance manager. The software Expert Choice (Ishizaka and Labib, 2009) was used as a support tool to implement the AHP-based approach with the aim of obtaining the relative weight of nodes and the global priority of assigned MKPIs. As expected, all pair-wise comparison matrices related to aspects were complete. As example, the following Figure 3 synthesizes results of Expert Choice as regards the level-1 nodes, whereas Figure 4 shows local priorities of nodes of level 2 related to the HSE being the latter the most important aspect among those of level 1.

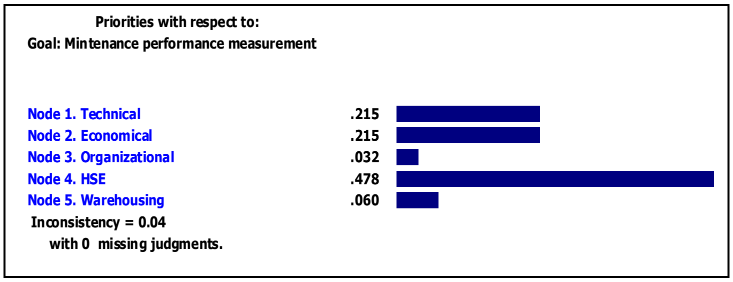

Figure 3 *Local Priorities of Level-1 Nodes*

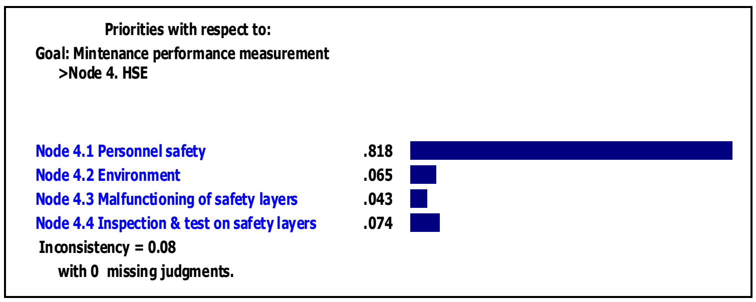

Figure 4 *Local Priorities of Nodes Related to the HSE*

As concerns pair-wise comparison matrices related to MKPIs, the iterative procedure synthesized in Figure 2 was implemented when necessary. For the sake of space and privacy as well, pair-wise comparisons between MKPIs are not hereafter reported. However, aiming at clarifying how the iterative procedure works and was implemented in the specific context, steps performed with relation to the node 5.2 are synthesized in the following as example. MKPIs assigned to such a node are reported in Table 4, whereas the related pair-wise comparison matrix elicited from the DM is shown in Table 5. The latter is incomplete since two judgments (i.e. elements c_{13} and c_{34}) are missing.

Table 4 *MKPIs Assigned to Node 5.2*

MKPI$_1$	Total cost of maintenance materials/Average inventory value of maintenance materials
MKPI$_2$	Total n° of spare parts not handled/Total n° of spare parts in stock
MKPI$_3$	Average inventory value of maintenance materials/Asset replacement value
MKPI$_4$	Total n° of non conforming spare parts/Total n° of spare parts checked in input

Table 5 *Pair-Wise Comparison Matrix between MKPIs of Node 5.2*

Node 5.2	$MKPI_1$	$MKPI_2$	$MKPI_3$	$MKPI_4$
$MKPI_1$	1	1/3	-	1/3
$MKPI_2$		1	1/3	4
$MKPI_3$			1	-
$MKPI_4$				1

Using the completion method of Harker, the obtained complete pair-wise comparison matrix is reported in Table 6.

Table 6 *Pair-Wise Comparison Matrix between MKPIs of Node 5.2 Completed by Harker*

Node 5.2	$MKPI_1$	$MKPI_2$	$MKPI_3$	$MKPI_4$
$MKPI_1$	2	1/3	0	1/3
$MKPI_2$	3	1	1/3	4
$MKPI_3$	0	3	3	0
$MKPI_4$	3	1/4	0	2

With the aim of performing the consistency check of pair-wise comparison matrix of Table 6, the related CI and CR were computed by using the RI parameter proposed by Forman (1990) for incomplete matrices of size four characterized by 2 missing judgments. The resulting CR was of 0.1891 which implies an unacceptable inconsistency. Therefore, the ε-method described in Section 4.4 was applied to find out the most inconsistent judgment of Table 6. The matrix $\boldsymbol{E}$ is shown in Table 7 where the value farthest from one is 1.663866, namely the greatest inconsistency arose from the element a_{24} of the completed matrix of Table 6.

Table 7 *Matrix E*

Node 5.2	$MKPI_1$	$MKPI_2$	$MKPI_3$	$MKPI_4$
$MKPI_1$	2	1.525641	0	0.634615
$MKPI_2$	0.655462	1	0.855742	1.663866
$MKPI_3$	0	1.168576	3	0
$MKPI_4$	1.575758	0.60101	0	2

On the basis of steps described in Figure 2, the element a_{24} was reformulated by the DM who suggests a new value equal to 2. The new consistency check returned a

CR equal to 0.0453 which implied an acceptable inconsistency. The following Figure 5 synthesizes local priorities of MKPIs assigned to the Node 5.2.

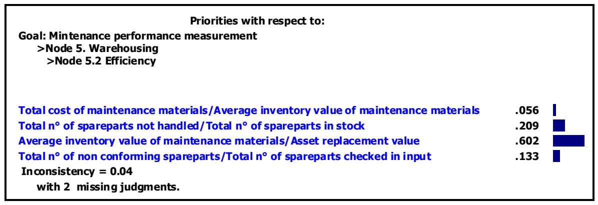

Figure 5 *Local Priorities of MKPIs of Node 5.2*

The global weights of MKPIs belonging to the Node 5.2 were obtained by taking the product of values reported in Figure 5 to the weights of Nodes 5.2 and 5.

As concerns the resolution of the model formulated to get the final optimal set of MKPIs, the commercial software Lingo was used. The parameters k_1 and k_2 were set by the DM equal to 0.6 and 0.4 respectively, whereas n_{min} was set equal to 2 for each level-1 node. Twenty-nine MKPIs were finally selected, 6 from the Technical node, 6 from the Economical node, 3 from the Organizational, 11 from HSE and 3 from Warehousing.

As aforementioned, the final list of MKPIs matches the specific requirements of the maintenance manager because it represents the best compromise between the information completeness and the computational effort required. Obviously, changing input parameters leads to a different optimal set of MKPIs. In this regard, a sensitivity analysis was firstly performed on the relative importance of the two terms of the objective function and then on the minimum descriptive ability required for each aspect of level one. As concerns the objective function, increasing values of k_2 lead to the selection of a smaller and smaller list of MKPIs in accordance with the constraint (7). Therefore, keeping unchanged the value of n_{min} (i.e. 2), the following results (Table 8) were obtained for different combinations of the objective function' weights.

Table 8 *Results of Sensitivity Analysis on the Objective Function' Weights*

k_1	k_2	Number of Selected MKPIs
0.9	0.1	54
0.8	0.2	39
0.7	0.3	30
0.6	0.4	29
0.5	0.5	18
0.4	0.6	18
0.3	0.7	17
0.2	0.8	17
0.1	0.9	14

As expected, the need at an operational level of a more detailed information (greater values of the parameter k_1) forces the model to select a more numerous set of MKPIs, with a consequent increase of the required computational effort.

Referring to the constraint (7), the greater the value of n_{min}, the greater the total number of selected MKPIs. Being n_{min} supposed to take the same value for each aspect of level one, n_{min} was changed from 1 to 4 in order to assure the feasibility of the model. Keeping unchanged the weights of the two terms of the objective function (i.e. k_1=0.6 and k_2=0.4), the following results (Table 9) were obtained for increasing values of n_{min}.

Table 9 *Results of Sensitivity Analysis Performed on the n_{min} Value*

n_{min}	Number of Selected MKPIs
1	27
2	29
3	31
4	33

Summing up, the sensitivity analysis highlights the flexibility of the formulated model that actually allows at considering the particular industrial context as well as it matches the stakeholder needs.

7. Conclusions

Nowadays, existing literature on Maintenance Performance Measurement (MPM) models and Maintenance Key Performance Indicators (MKPIs) principally lacks on two aspects. Firstly, proposed MPM frameworks are generic and disregard the business specific environment of the company wherein these tools should be applied. Then, the available literature proposes a huge list of MKPIs but it does not contain any methodological approach for selecting or deriving specific MKPIs from the listed indicators. With these recognitions, the novel contribution of the work was the proposal of a structured methodology for the MPM by means of a restricted and comprehensive list of MKPIs. The approach was designed with relation to an oil refinery plant and arose from the real need of the maintenance manager to measure, monitor and communicate the maintenance process results to both the board and the maintenance technicians on the basis of different perspectives. The subject company maintenance staff was actively involved in the definition and implementation of the whole methodology. Firstly, a customized multi-level and multi-node hierarchical framework able to synthesize the most meaningful aspects affecting the effectiveness and the efficiency of the maintenance process was designed. Then, MKPIs already proposed by the technical and scientific literature were collected and analyzed in cooperation with the subject company maintenance staff in order to identify and select the most appropriate to describe the specific maintenance process. In addition, several indicators were formulated *ad-hoc* and consequently assigned to nodes of the hierarchical framework together with those previously selected from the literature. Aiming at ranking the assigned MKPIs, an Analytic Hierarchy Process (AHP)-based approach with incomplete pair-wise comparison matrices was successively implemented and an iterative procedure properly designed to improve the pair-wise comparison matrices consistency. Finally, a mathematical programming model was formulated in order to select the optimal set of MKPIs.

Summing up, the main attempt of the work was to fill a gap in the literature of a structured approach able to guide the DM in all stages of the decision-making process addressed to a synthetic evaluation of the maintenance performance. Starting from the preliminary phase of identification of the main perspectives that affect the maintenance performance, the development of the hierarchical structure forces the DM to a more detailed analysis of the decisional problem and facilitates the choice of the most suitable MKPIs to describe such perspectives. During the next stage when the assigned MKPIs are assessed on the basis of their descriptive ability, the procedure allows the DM at expressing also incomplete information and improving its consistency as well. Finally, the mathematical programming model leads to the selection of the optimal set of indicators based on specific requirements of the DM as concerns the global descriptive ability as well as that related to the first level aspects of the hierarchical structure.

Even if designed with relation to a high risk process plant, the proposed methodology may be implemented in other industrial contexts after a properly customization of the hierarchical framework.

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