Investigating the impact of social sustainability within maintenance operations

An action research in heavy industry

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Abstract

Purpose – The purpose of this paper is to primarily focus on labor in maintenance areas, addressing human rights issues, labor standards and safety standards. The main issue is to investigate how these factors are considered to drive the prioritization of maintenance interventions within maintenance plans. In particular, a method for criticality analysis of production equipment is proposed considering specific labor issues like age and gender, which can be useful to steer maintenance plans toward a more social perspective.

Design/methodology/approach – The authors focus on the two main social issues of SA 8000 norms, age and gender, exploring how these issues may drive the selection of maintenance policies and the relative maintenance plans. The research is conducted through fuzzy analytical hierarchy process (AHP) implemented within a failure mode effects analysis (FMEA).

Findings – The research is conducted through fuzzy AHP implemented within a FMEA. The maintenance plans resulting from the FMEA driven by social issues are evaluated by a benchmark of three different scenarios. The results obtained allowed the firm to evaluate maintenance plans, considering the impact on workers' health and safety, the environment, social issues like gender and age.

Research limitations/implications – One of the main limitation of this research is that it should also encompass maintenance costs under social and safety perspective. The method developed should be extended by further study of maintenance planning decisions subject to budget constraints. Moreover, it would be worth evaluating the effect of adopting more proactive maintenance policies aimed at improving plant maintainability in view of what emerged during the test case in the presence of an aged workforce and the subsequent need to prevent and/or protect people from hidden risks.

Practical implications – With reference to the results obtained from the two models of this scenario, the authors observed an increase of equipment criticality, from B class to the A class, and similarly from C class to B class. No equipment has reduced its criticality. This depends on the particular context and the relative weights of drivers indicated in its AHP matrixes.

Social implications – The paper addressed the main social implication as well as other social issues represented by age and gender factors, which are normally neglected. The Action Research (AR) proved the effects resulted from considering either gender factor or gender and age factors at the same time for maintenance policy selection. All in all, an increase of criticality is evident even if "people" is a driver with less importance than "environment" and "structures."

Originality/value – The present work focussed on a new definition of a criticality ranking model to assign a maintenance policy to each component based on workers' know-how and on their status. The approach is conceived by the application of a fuzzy logic structure and AHP to overcome uncertainties, which can rise during a decision process when there is a need to evaluate many criteria, ranging from economic to environmental and social dimensions.

Keywords Analytical hierarchy process, Maintenance management, Fuzzy logic, SA 8000, Social issues

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1. Introduction

The concept of sustainable development gradually started to enter the corporate management lexicon (Seuring *et al.*, 2008) as a relevant driver of on-going transformation with an awareness of environmental and social impact of industrial activities (Evans *et al.*, 2009; Zellner and Reeves, 2010). Recently Garetti and Taisch (2012) indicated environmental, social and economic dimensions as the key challenges that sustainable manufacturing must respond to. The trend toward industrial sustainability is observed in many areas and is discussed in various roadmaps. Under this perspective, at the European level, it is worth mentioning manufacture (Jovane *et al.*, 2009), IMS2020 (2009) and the work of Sohail *et al.* (2005) on sustainable operations and maintenance of urban infrastructure. These authors widely acknowledge the requirement of a shift in managerial and methodological approaches, and integration of sustainability in new business models (Liyanage, 2007; Garetti and Taisch, 2012). Two issues in particular are addressed: the need for a more holistic view of value creation integrating social and environmental goals (Schaltegger *et al.*, 2011); the scope of value creation including a wider range of target stakeholders within business ecosystem (Allee, 2011). Indeed, stakeholders have become a common issue discussed in business theory "since the publication of Freeman's landmark book, *Strategic Management: A Stakeholder Approach*" (Donaldson and Preston, 1995). Freeman (1984) defined stakeholders of a company as "any group or individual who can affect or is affected by the achievement of the organisation's objectives" (Freeman, 1984). According to Clarkson (1995), stakeholders can be categorized into groups. Employees, on which the present paper particularly focusses, are among the primary stakeholder groups.

This work considers sustainability in industry as a background. It focusses on the contribution of maintenance as a possible relevant activity for improving sustainable value creation within a production system. Company employees are considered as a specific target of sustainable value creation. The impact of social issues is to explore with a proactive approach which employees may be considered as stakeholders of the company.

Management and labor are components of this stakeholder group, while their stakes are related to a wide number of sustainability factors, such as labor standards, human rights issues, laws and regulations, diversity and equal opportunity, training and career development and engagement with the wider community (Elkington, 1997; Labuschange *et al.*, 2005; Elliot, 2006). The present work is primarily focussed on labor in maintenance areas, addressing human rights issues, labor standards and safety standards. The main issue is to investigate how these factors are considered to drive the prioritization (criticality classes) of maintenance interventions within maintenance plans. In particular, a method for criticality analysis of production equipment is proposed considering specific age and gender issues, which can be useful to steer maintenance plans toward a more social perspective. The method is developed within the framework of failure mode effects analysis (FMEA) methodology, resulting in a FMEA that integrate social issues.

The paper is organized as follows. Section 2 analyzes current engineering approaches for maintenance policy selection and planning, with special focus on economic, environmental and social dimensions; specific attention is given to standards, dealing with the environmental and social dimensions. The research propositions and framework are presented in Section 3, while Section 4 describes the method for criticality analysis of production equipment, as well as the mathematical fuzzy model for maintenance policy selection with social and environmental issues. Sections 5 and 6 motivate the action research to address the research propositions in practice, with its results. Section 7 discusses the practical implications of the results obtained, while the discussion remarks of the research work are reported in Section 8. Section 9 concludes the work, giving its limitations and possible future insights.

2. Literature review

Nowadays academics and managers acknowledge the importance in supporting production and maintenance engineers in technical and economic supervision of production and maintenance activities (Jasiulewicz-Kaczmarek, 2013). In this context, Crespo Marquez and Gupta (2006) identified maintenance engineering (ME) as one of their three pillars, envisioning engineering activities, tools and techniques needed for keeping and improving maintenance effectiveness and efficiency (Crespo Márquez *et al.*, 2009). In the perspective of this paper, ME has the leading role to generate maintenance plans not only through the control of technical and economic indicators, but also with respect to other ethical and social issues. With this purpose, ME applies specific techniques to analyze field data, technical information and documents, as well as to develop maintenance plans according to norms and regulations adopted as guidelines (Figure 1).

Recent additional surveys (Chinese and Ghirardo, 2010; Chinese *et al.*, 2011; Macchi *et al.*, 2012) reveal that the concepts of ME may not be operating effectively in many firms. The above authors demonstrate that majority of smaller firms show weaknesses in maintenance function, due to inadequate diffusion and use of ME planning and control tools such as computerized maintenance management system, whereas this last one is better developed among big firms, above all engineering ones.

In this context, maintenance includes technicians, engineers and managers in the definition of appropriate maintenance policies for a certain equipment, based on criticality analysis and further ranking in line with company's objectives (Faccio *et al.*, 2014). Moreover, maintenance function requires the design of medium- and

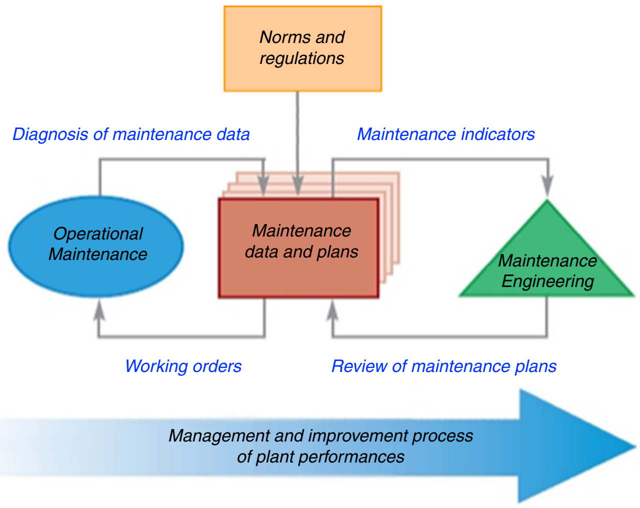

Figure 1. Maintenance management as continuous improvement of plant performances

long-term plans embracing safety norms and regulations, safeguarding workforce health and environmental protection that are based on both company's rules and existing standards.

2.1 Standards adopted as a reference

This work adopts three SI to guide the determination of criticality classes and the design of maintenance plans: social accountability (SA) 8000, OHSAS 18001, ISO14001.

Social Accountability International is a non-profit human rights organization founded in 1997 with the aim of improving workplaces by developing and implementing a socially responsible standard, i.e. SA 8000 (SAI, 2008a). SA 8000 covers human rights issues including in particular child labor and health and safety (SAI, 2008b). It defines as child any person under 15 years of age, unless the minimum age for work is defined differently by local laws, whereas young worker means any worker over the age of a child and under the age of 18. The main purposes are to fight child and forced labor; to provide a safe and healthy workplace; to assure compliance with laws and industry standards in terms of working hours.

In this context, two pioneering approaches can be the one of Persona *et al.* (2010), regarding the age replacement policy in operations management and the one of Sgarbossa *et al.* (2014) that uses the systemability function to define feasible workers replacement policies.

Under safety perspective, OHSAS 18001 regulates the implementation of a management system to ensure safety control and healthcare conditions. This standard stipulates norms for a structured approach to planning, implementing and following up a management system in which a document of risk evaluation plays the essential roles of analyzing activities implemented within the organization and the respective risks; and identifying preventive and protective actions and tools for continuous improvement of safety and healthcare.

By environmental side, ISO14001 is a standard defining a comprehensive environmental management system, enabling organizations to formulate corporate objectives and helps each complying organization to define its environmental policies clearly (Howe, 1997). Link and Naveh (2006) stated that if ISO14001 requirements become part of the organization's daily practices, standardization of the organization's handling of environmental issues follows, leading consequently to better organizational environmental performance.

2.2 ME approaches

Different measures can also be considered for the selection of maintenance strategy, with the aim to better align business success of organizations (Tsang, 2002). Triantaphyllou *et al.* (1997) suggested a maintenance strategy covering reliability, but also cost, reparability and availability. By applying reliability, availability and maintainability techniques, it is possible to limit faults occurrence by appropriate time-based maintenance intervals according to cost optimization models (Moubray, 1991) through the analysis of historical data set of failures. Among traditional approaches, it is worth mentioning failure mode effects and criticality analysis (FMECA – Tsakatikas *et al.*, 2008) as one of the elective techniques of reliability-centered maintenance (RCM) methodology (Rausand, 1998), whose priority number drives maintenance policy selection and planning. Mahadevan *et al.* (2010) described a maintenance context and component substitution with the aim to minimize maintenance costs and times. Li *et al.* (2011) defined an Artificial Fish School Algorithm based on ant colony model for preventive maintenance optimization related to component aging. Other results regarding the application of artificial intelligence techniques within ME can be retrieved in Brun *et al.* (2011) and Kobbacy and Vadera (2011).

Recently, new maintenance policies have emerged to optimize preventive maintenance activities with reference to risks and cost-effective analysis (Yufan *et al.*, 2011). According to Ghosh and Roy (2010) budget limits are the first drivers but safety, maintenance investments, feasibility and production stops must be considered to select maintenance policies.

Approaches purely based on safety risk evaluation and environmental aspects can be found as well. With reference to safety risk evaluation, maintenance methods based on risk assessment can be cited. Hauge and Johnston (2001) incorporated a risk assessment tool in the RCM approach for shuttle ground support equipment and facilities maintenance. Arunraj and Maiti (2007) stated that an effective use of resources can be achieved by using risk-based maintenance decisions to guide where and when to perform maintenance. They provided a literature review of the state of the art, making it clear that performance of risk analysis and risk-based maintenance strongly depend on the depth of analysis, area of application and expected quality of results. Ghosh and Roy (2010) affirmed that attributes, such as maintenance investment, business interruption loss, feasibility and safety must be considered, first of all when equipment is ranked according to a risk-based assessment. Jiejuan *et al.* (2004) presented a conceptual feasibility investigation for the development of a genetic algorithm to solve a risk-cost maintenance model. Krishnasamy and Haddara (2005) proposed a risk-based maintenance procedure based on the optimization of the inspection interval. Risks were calculated as a function of the failure probability and through a fault tree technique. Marmo *et al.* (2009) developed a procedure consisting of a risk-based approach to optimize maintenance scheduling.

Models combining more than one aspect related to mere safety or reliability have also been developed. Bevilacqua and Braglia (2000) based their model on four criteria: cost, damages, applicability and added value. Bertolini and Bevilacqua (2006) took into account failure occurrence, severity and detectability, while Arunraj and Maiti (2007) and Carazas and Souza (2010) developed their selection model in relation to risk contribution of equipment and costs of maintenance policy. Wang *et al.* (2007) proposed a model based on safety, added value, cost and feasibility drivers. More in general, Bashiri *et al.* (2011) identified quantitative and qualitative criteria for selection of the most suitable maintenance strategy.

2.3 Analytical hierarchy process (AHP) and fuzzy set approaches in ME

Because of its multiple drivers, maintenance strategy selection counts as a multi-criteria decision-making (MCDM) problem, whose AHP is one of its most popular resolution tools (Wang *et al.*, 2007; Savino *et al.*, 2012). AHP consists in a decision-support procedure for dealing with complex, unstructured and multiple-attribute decisions aimed at identifying priorities or weights (reflecting importance) to be assigned to the different criteria that characterize a decision (Saaty, 1990; Dey, 2004). Bevilacqua and Braglia (2000) applied AHP for maintenance strategy selection by considering five alternative maintenance policies: preventive, predictive, condition based, corrective and opportunistic. Bertolini and Bevilacqua (2006) extended the application of AHP to define priorities for classical parameters of FMECA priority numbers, to drive the final selection of the best maintenance policies. Ierace and Cavalieri (2008) used the same criteria to support the selection maintenance of strategy in automotive sector. Their specific concern, among the alternatives, was the evaluation of a thermography technique for condition-based and predictive maintenance. Arunraj and Maiti (2010) used a similar approach taking the risk of equipment failure and cost of maintenance policy to the second level of the AHP hierarchy. All in all, since the late 1990s MCDM has gained relevance in maintenance strategy selection, as can be observed by other research works applied to different industries (De Almedia and Bohoris, 1995; Triantaphyllou *et al.*, 1997; Labib *et al.*, 1998). In addition, fuzzy logic is applied further to overcome uncertainties characterizing the decision process with AHP methodology. Fuzzy sets theory can adequately model processes where observed data are uncertain, vague and/or subject to human perceptions (Faraz and Shapiro, 2010; Shafiei-Monfared and Jenab, 2012). Consequently, fuzzy numbers are obtained for a fuzzy ranking procedure of critical components (Wang *et al.*, 2007), or to apply a relative membership grade in solving a multi-criteria decision problem to select the most appropriate maintenance policy (Peng and Wang, 2011). Still concerned with fuzzy sets, Al-Najjar and Alsyouf (2003) used past data and technical analysis to process machines and components in a fuzzy inference system to assess the capability of each maintenance approach. Jafari *et al.* (2008) applied a fuzzy method to solve maintenance strategy selection problems to satisfy each maintenance goal, whereas Brun *et al.* (2011) applied FMECA and a fuzzy inference engine for a safety-oriented maintenance model. Wang *et al.* (2007) proved the benefits for plant maintenance managers through an MCDM problem and a fuzzy-AHP method.

3. Research propositions and framework

3.1 Research propositions

The main scope of the present research is to explore the influence that social aspects may have in the definition of criticality classes of the functional assets, and hence their maintenance policies.

In the first part of the work, the research methodology applies AHP to define the relative importance of social issues as additional maintenance drivers. Then, by FMEA we develop the criticality analysis for all the components of the plant. The method results in a new joint AHP/FMEA methodology in which tables and interviews are the main operative tools for criticality analysis.

The whole research methodology is designed to investigate the following propositions:

P1. A proactive approach is necessary for fair management of firm activities, in particular for maintenance ones, covering not only compulsory norms or regulations. Requirements of international standards (IS) and modern industrial contexts may include social drivers. Consequently, the methodology is designed to use IS as a reference and to integrate them with the requirements identified within the industrial activities. Introduction of social issues as an additional driver allows to include an aspect generally considered as marginal as regards to its contribution to safety. Indeed, today's risk-based maintenance already focusses on the importance of workplace safety, but it neglects value opportunities that can be captured by a more proactive approach that includes social aspects.

P2. SA can be integrated into maintenance models considering environmental, safety and economic features. As safety is clearly a matter of fact in firm management, additional factors could be introduced improving the attitude toward protection of workplaces and workforces, distinguishing them between men, women and young workers. Such factors should be found within the social driver. IS, like SA 8000, can be helpful to identify factors within social drivers.

P3. Among social issues, gender and age are the most representative, affecting the definition of maintenance plans. In this work we aim to drive maintenance managers in considering workers as firm's stakeholders with two social attributes, gender and age. The action research supported us into the selection process of such innovative features, that were shared with managers after brainstorming and interviews. Considering such attributes, the work of maintenance managers should accomplish better labor standards and human rights, taking care of workers with their own features and stakes. If gender attribute is proposed by SA 8000, age factor is not explicitly included in any norm. Nonetheless, it may assume great importance within maintenance operations, as it is better discussed in the next section.

3.2 Research framework

Figure 2 provides a structured overview of the research framework, where social issues are considered as an potential maintenance driver. Through the combined AHP/FMEA this framework explores: how maintenance policies may be influenced by the introduction of this potential maintenance driver; and how all maintenance drivers may be reorganized in a criticality analysis.

The output of the combined AHP/FMEA is to investigate how the criticality analysis of all the components of the plan may be affected by the impact of social aspects, in terms of age and gender of the workers.

The model is validated within an industrial context according to action research principles, borrowing FMEA methodology for line-replaceable-units (LRU) components.

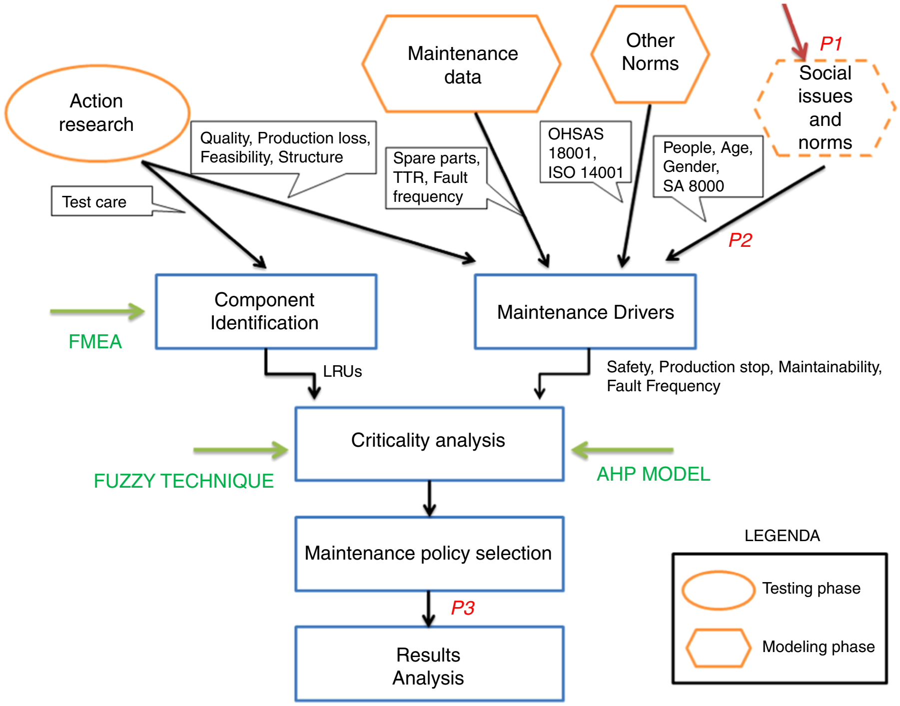

Figure 2.
The research methodology

These components are involved in criticality analysis, where *P3* ensures a throughout and fair analysis of results.

According to FMEA principles, equipment can be identified through a functional decomposition of the plant, referring to technical manuals and leveraging of the technicians'/employees' know-how, to provide a hierarchical tree structure of components. LRU criteria are used to stop the decomposition process. As per FMEA, LRU are those units replaced on production line by maintenance operators. Then, an equipment criticality ranking procedure is performed on LRU through AHP method based on a set of drivers.

4. Criticality ranking and maintenance policy selection

4.1 Method for criticality ranking and maintenance drivers

We divided the criticality ranking in two steps:

1. Collection of the functional data for each LRU. The collection is relative to: faults indicators: frequency, MTBF, MTTR; costs indicators: production losses, additional costs generated by a fault, cost of spares, number of defective parts, waste assessment, external maintenance interventions; safety.
2. Development of the AHP model. In this step, two levels are introduced. A criteria level (upper) and a further sub-criteria level (lower).

Specifically, the upper level relates to: safety of people, environment and structure-firm assets; production stop and related losses; maintainability, regarding to the possibility of equipment restoring through a maintenance intervention; fault frequency.

Except for fault frequency, a lower level is considered for better specification of a set of main features for the upper level, which led to the following maintenance drivers as sub-criteria:

1. production stop: spare parts, production losses and quality of process/product; and
2. maintainability: time to repair, economic and technical feasibility of maintenance activities.

In terms of social aspects, the new model adopts the SA 8000 standards, thus introducing the following three parameters:

1. people safety, possible damages to structures, environment;
2. age of maintenance staff; and
3. gender of maintenance staff.

As regards to safety evaluation and health prevention, the alternatives for the sub-criteria people are defined through interviews to workers and managers as: low risk: no danger to employees; medium risk: possible danger to employees; high risk: danger to employees. The risk evaluation is borrowed from risk analysis data available within the firm.

Age can impact on equipment criticality ranking, because for some maintenance activities particular skills can be necessary related to working experience. In this sense, we considered that aged workers can be somewhat favored. Such consideration is shared with maintenance managers and employees where the AR was developed. The interviews revealed how often skill and experience of aged workers may carry the following hidden risk: excessive self-confidence can lead to underestimation of real safety risks. This may even lead to not following elementary safety procedure provided within the risk assessment document. With reference to maintainability, age can have a positive influence, owing to the greater experience generally associated with advanced age, but it can also become an obstacle in terms of self-confidence or tough maintenance operations. With this aim, two criticality classes represent the alternatives for the sub-criteria age, according to the working life of the maintenance workforce: low risk: middle working life; high risk: young and old working life. The boundaries of young and old working life should be defined according to the specific industrial context and to maintenance operations. In our case, according to maintenance manager interviews, a young working life is set at less than seven years, while old working life is higher than 25 years.

Figure 3 reports the AHP hierarchy, detailing goals, criteria and alternatives with the possible outputs of the procedure, in terms of criticality classes of the components maintained. In Figure 3 the AHP hierarchical structure shows the relationship between the goal, primary criteria, sub-criteria and alternatives, according to Arunraj and Maiti (2007) representation.

In Figure 3, gender criteria are also detailed. For this aspect, we took inspiration by the work of Brun *et al.*, as regards to the possible change of risk levels due to the presence of women/young workers. A survey among the workers has been conducted for social issues criteria, obtaining the following risk levels: low risk: no danger for employees; average risk: possible danger; high risk: in case of possible danger for female or young employees.

Particularly, goal, criteria and alternatives are highlighted while the definition of the pairwise comparison matrix and the relative weights are described in Sections 5.2 and 4.2, respectively, through the direct reference to the case study.

Age and gender are included in the model for the selection of the maintenance policy and definitely affect the results of the model as it will be clear in the section results.

The output of the model is represented by three classes of criticality which can be assigned to the assessed equipment:

(1) A class, high risk;

(2) B class, medium risk; and

(3) C class, low risk.

A maintenance policy (Ahmad and Kamaruddin, 2012; Ghosh and Roy, 2010) is associated with each class: A class with predictive maintenance, B class with time-based preventive maintenance, C class with corrective maintenance.

Such output is obtained through the development of the model combining AHP and fuzzy described in the next section.

4.2 Fuzzy model for maintenance policy selection

Fuzzy decision matrixes is compiled according to the interviews conducted with maintenance employees and technicians, on the basis of the importance of one driver with respect to another for the achievement of the given goal of "maintenance policy selection." Each evaluation is translated into a fuzzy triangular number (l_{ij}, m_{ij}, u_{ij}) where $l_{ij} \leqslant m_{ij} \leqslant u_{ij}$. Table I reports values of the comparison matrixes.

The same procedure is used to compare matrixes of lower levels. Thereafter, to assign a criticality class for each part of the equipment.

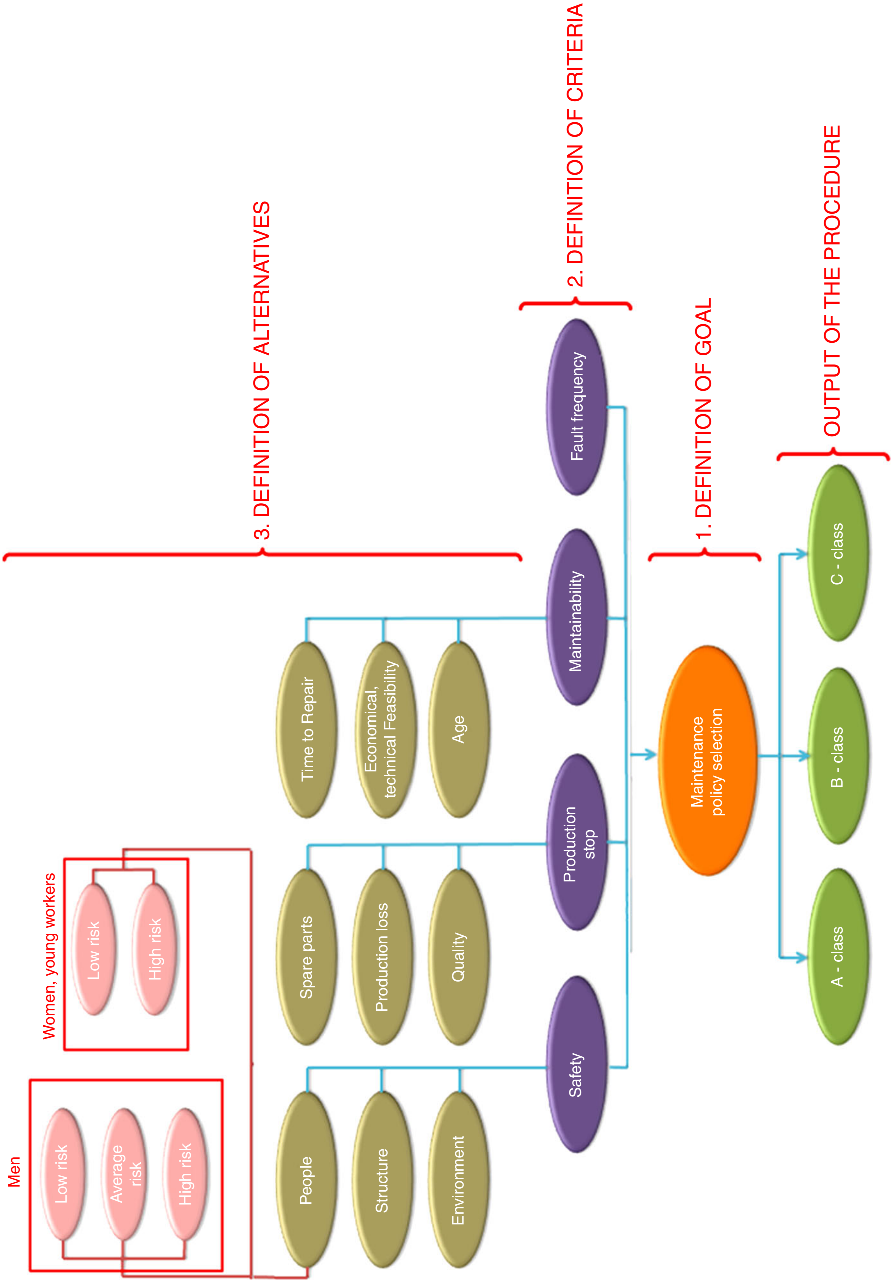

Figure 3.
AHP hierarchy for maintenance activity planning

These matrixes provides the crisp priority vector (CPR) $w=(w_1, w_2, \ldots, w_n)^T$, that represents the importance assigned to each criterion "*i*" and sub-criterion "*j*." Within the CPR, w_i, w_j values reflect the following priority $\frac{w_i}{w_j}$ ratio subject to the constraint: $l_{ij} \leqslant \frac{w_i}{w_j} \leqslant u_{ij}$.

With respect to the $\frac{w_i}{w_j}(i \neq j)$ ratio, the membership function is defined according to the approach of Wang *et al.* (2007). Together with a consistency analysis of values, priority evaluation is performed by the following constrained optimization problem (Equation (1)):

$$\begin{aligned} \min J(w_1, w_2, \ldots, w_n) &= \min \sum_{i=1}^{n} \sum_{j=1}^{n} \left[\mu_{ij}^{p}\left(\frac{w_i}{w_j}\right) \right] \\ &= \min \sum_{i=1}^{n} \sum_{j=1}^{n} \left[\delta\left(m_{ij} - \frac{w_i}{w_j}\right) \left(\frac{m_{ij} - \frac{w_i}{w_j}}{m_{ij} - l_{ij}}\right)^{p} \right. \\ &\quad \left. + \delta\left(\frac{w_i}{w_j} - m_{ij}\right) \left(\frac{\frac{w_i}{w_j} - m_{ij}}{u_{ij} - m_{ij}}\right)^{p} \right] \end{aligned} \tag{1}$$

subject to:

$$\text{(i)} \sum_{k=1}^{n} w_k = 1; \text{(ii)}\ w_k > 0, \text{where}\ i \neq j,\ p \in N,\ k = 1, \ldots, n,\ \delta(x) = \begin{cases} 0 & x < 0 \\ 1 & x \geqslant 0 \end{cases}$$

The mathematical solver implemented in Matlab (2015) gives the following output: w_i, corresponding weight to each criterion "*i*"; w_{ij}, corresponding weight to each criterion "*i*" and sub-criterion "*j*"; w_{ijk}, corresponding weight to each criterion "*i*," sub-criterion "*j*" and alternative "*k*"; W_{Ck}, corresponding weight to each criticality class C of alternative "*k*": $C \in \{A, B, C\}$. According to the previous weights, it is possible to evaluate a global score for each maintenance approach (Equation (2)) as:

$$SCORE_{AHP\ i\text{th}\ class} = \sum_{k} (W_k \times W_{Ck}) \text{ with } W_j = w_{ij} \times w_i \forall j \text{ and } W_k = w_{ijk} \times W_j \forall k \tag{2}$$

where W_j is the global weight of sub-criterion "*j*" and W_k is the global weight of alternative "*k*." A higher AHP score suggests the respective higher class of the equipment and the corresponding maintenance policy to be adopted.

Then, the extended AHP model is implemented in Matlab (2015), with a routine that processed the data of the matrixes to evaluate the CPR. Then, the prototype software

Table I.
Fuzzy numbers generation through triangular function

Evaluation	Fuzzy number
Seldom equal	(0.5, 1, 2)
Around *x* times more important	(*x*−1, *x*, *x*+1)
Around *x* times less important	(1/(*x*+1), 1/*x*, 1/(*x*−1))
Between *y* and *z* times more important	(*y*, (*y*+*z*)/2, *z*)
Between *y* and *z* times less important	(1/*z*, 2/(*y*+*z*), 1/*y*)

computes maintenance class with Equation (2), prior verifying the consistency of the obtained values. In the algorithm below, we report the Matlab code for the evaluation of the objective function *J*.

Code for objective function computing:

```
for i=1:criteria
     for j=1:criteria
            x1=mij(i,j)-(x(i)/x(j));
            x2=(x(i)/x(j))-mij(i,j);
        if (x1<0)
          delta1=0;
        else
          delta1=1;
        end

        if (x2<0)
          delta2=0;
        else
          delta2=1;
        end
        J=J+delta1*(x1/(mij(i,j)-lij(i,j)))^p+delta2*(x2/
(uij(i,j)-mij(i,j)))^p;
        end
     end
 end
```

5. Motivations of action research

This study is carried out using AR as empirical methodology for applying, testing and evaluating the adequacy of FMEA methodology integrated with social issues. The AR also aims at evaluating the effective support of the proposed to industrial decision makers. AR allows on-field analysis of the phenomena including not only quantitative data, but also qualitative data and subjective aspects, essential to establish the particular circumstances of the industrial case. As a result of AR adoption, research and industrial practice are merged, with the benefit of relevant findings (Baskerville and Pries-Heje, 1999). According to Coughlan and Coghlan (2002) AR has several broad characteristics; among which: a focus on active work of researchers aimed at making the action happen; a participative methodology, leveraging tight collaboration among researchers and industrial personnel. Collaborative work is considered as an essential source of knowledge for the particular innovation undertaken during this work. In-depth study of industrial needs was possible, with the benefit of consistent development of the approach proposed in Section 3. AR also enabled testing of the theory developed during the research, gathering of feedback on expected implications which are discussed further on in the seventh section of the paper in relation to the theoretical model developed to integrate the social issues, with subsequent implications for industrial actions.

5.1 The action research

A production line of panels or beams is considered as test case. Maintenance activities of cutting center and related conveyor is analyzed for model validation. In this context a small percentage of female workforce is employed for maintenance operations.

The automatic cutting center performs transversal and angular cuts on a cement plate, while longitudinal ones are performed by moving the plate at a variable speed.

The conveyor line (Figure 4) is composed of an input and an output conveyor, and a set of equipment, identified by numbers from 1 to 7, where: 1 – input conveyor; 2 – conveyor toward cutting zone; 3 – output conveyor; 4 – side output; 5 – chain conveyor; 6 – stairs; 7 – maneuvering seat.

5.2 FMEA and fuzzy-AHP criticality analysis

This phase of the action research is composed in three steps. The first step consists of functional decomposition of the work-centers in LRU, with the FMEA analysis. The second step regards the construction of the matrixes of the fuzzy-AHP method. Then, in the third step we apply Equations (1) and (2) to define the AHP score for each equipment of the plant.

First step – functional decomposition and failure analysis. The functional decomposition is developed with the basic design and maintenance data of the plant, basically: machining centers and equipments. Then, for equipment the bill of materials is developed to obtain the functional decomposition.

Table II shows an extract of the functional decomposition for the cutting center equipment, in which identification numbers and codes of the functional assets are assigned to each machine.

Failure analysis is then conducted within the functional decomposition for each functional asset.

The failure mode analysis of these functional assets is characterized by the following features: production stop interval due to maintenance intervention; failure frequency, relative severity and safety problems; MTBF and MTTR; spares availability; weak signals for failures detection; production losses, additional costs of a fault, waste, external maintenance activities; spares cost.

The analysis is conducted by interviews, meetings and brainstorming with technicians, to carry out a complete data analysis and to compile AHP matrixes.

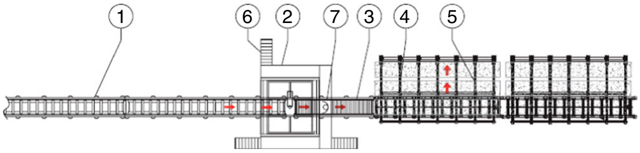

Figure 4.
Conveyor line

Table II.
Functional decomposition of the cutting center

			Machine: cutting center		
Machine	No.	Cod.	Functional asset	Cod.	Equipment
Automatic cutting machine	1405/08	1	Castle	1	Diamond disc
				2	Belt
				3	Support
				4	Bearing
				5	Held
		2	Translation group	1	Joint
				…	…

The main output of the this step is the characterization of each equipment in terms of the drivers selected for the AHP model.

Second step – fuzzy-AHP matrixes. The matrixes relative to the development of the second step are given for people, age and gender drivers.

In Table III we report the first comparison matrix, relative to the importance of people, environment and structure drivers toward safety.

Within this step, Tables IV and V report the comparison matrixes relative to the goal maintainability involving the factor age and factor gender, respectively.

Third step – AHP score for plant equipments. According to the mathematical model of Section 3.2, the (1) is applied to the CPR of the AHP matrixes. Then, with (2) we obtain the AHP values for each equipment of the plant. Table VI shows an extract of values obtained by the AHP method for the cutting machine equipment. A global score referring to A, B, C criticality classes is obtained, higher values indicate the criticality class (e.g. B class as in Table VI) for each equipment of the plant.

6. Results

The results obtained with the extended model are compared with a similar version of the model where social issues are neglected.

The comparison has been conducted with a "reduced" AHP model in which we excluded the parameters age, and gender of the workers.

Figure 5 shows the percentage of equipment grouped in A, B and C classes, thus providing a comparison between the extended model driven by social issues and the reduced model.

For both models, less than 10 percent of equipment belongs to the A criticality class because of its high fault frequency and risk. The remaining equipment is almost equally divided among criticality classes.

Safety	People	Environment	Structure
People	(1, 1, 1)	(1/6, 1/5, 1/4)	(1/6, 1/5, 1/4)
Environment	(4, 5, 6)	(1, 1, 1)	(2, 3, 4)
Structure	(4, 5, 6)	(1/4, 1/3, 1/2)	(1, 1, 1)

Table III.
Comparison matrix for people driver

Maintainability	Time to repair	Tech. feasibility	Age
Time to repair	(1, 1, 1)	(1/4, 1/3, 1/2)	(1/5, 1/4, 1/3)
Tech. feasibility	(2, 3, 4)	(1, 1, 1)	(1/3, 1/2, 1)
Age	(3, 4, 5)	(1, 2, 3)	(1, 1, 1)

Table IV.
Comparison matrix for age driver

Maintainability	MTBF	Production loss	Gender
MTBF	(1, 1, 1)	(1/8, 1/5, 1/6)	(1/6, 1/6, 1/5)
Production loss	(3, 4, 6)	(1, 1, 1)	(1/5, 1/4, 1)
Gender	(3, 5, 6)	(2, 4, 5)	(1, 1, 1)

Table V.
Comparison matrix for gender driver

Table VI.
Classification for cutting machine

	Wk	A class	B class	C class
Low risk – people	0.027	0.325	0.334	0.341
High risk – people	0.022	0.389	0.440	0.171
Structure safety	0.108	0.389	0.460	0.171
Environmental safety	0.106	0.389	0.440	0.171
Stock part	0.070	0.350	0.339	0.318
Production loss	0.055	0.343	0.410	0.318
Quality	0.083	0.343	0.339	0.319
Low risk – age	0.156	0.340	0.354	0.301
High risk – age	0.040	0.310	0.320	0.360
Time to repair	0.107	0.343	0.339	0.318
Ec. and tech. feasibility	0.133	0.343	0.339	0.318
Failure frequency	0.258	0.364	0.320	0.317
AHP score		0.394	0.401	0.314

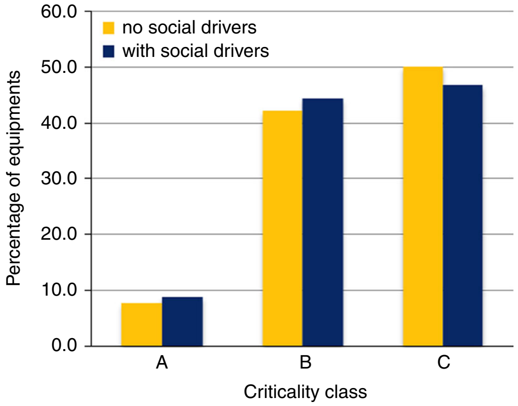

Figure 5.
Equipment classification considering age and gender – first scenario

A further analysis aimed at analyzing the impact of single aspects of age and gender in heavy industry environment, characterized by a low percentage of women/young workers. Figure 6 shows a comparison between the reduced model and a model excluding the age factor. Hence, it is labeled "only gender" for this second scenario, evaluating gender with respect to age.

For the specific test, but more generally because of the lack of women or young labor in heavy industries, results are meaningful: gender can be almost neglected, whereas age cannot.

7. Practical implications

The values of the matrix of Table III may remark the importance given by the firm in environmental policies. The values of this matrix may conduct us the consideration that environment is considered between five and three times more important than people and structure, respectively, mainly because nowadays ISO14001 certification is considered as a must. Yet, the results must be considered in relation to the equipment analyzed.

Although the industrial project was intended to raise awareness of the importance of social aspects, people are still considered of less importance than environment

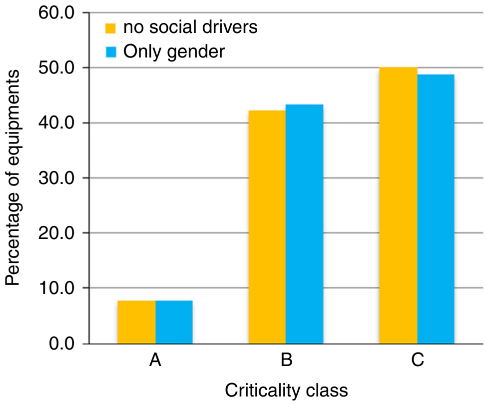

Figure 6.
Equipment classification considering only gender – second scenario

and structure. This is a particular situation, contingent on the context of the AR, and affecting results and discussions. Another interesting implication of the matrixes analysis is the age and gender factor over maintainability features.

The main interesting implications of these age analysis are that: first, the age of the workers involved in maintenance affects the technical feasibility on the maintenance intervention; and second, the age of the workers may extend the time to repair of the equipment. This last implication may be addressed not to social issues, but mainly to the experience of the worker, that increases with the age.

The main social implication of the analysis may be addressed to the gender issue, that is considered on the same level of production loss and MTBF. This may conduct us to the consideration that the gender issue of the worker may affect the MTBF factor. Yet, the gender of the workers may affect the criticality class of the equipment more than MTBF values. Based on these values, we may expect a higher influence of age as regards of gender in determining the criticality class of the components.

Then, based on the results of the AHP classification, we may assert that the two main social drivers analyzed affect the criticality classes of the plant equipments mainly for the A and B classes. This may conduct us argue the implication that for non-critical equipment the social drivers may be neglected in heavy industry. Moreover, by considering only the gender issue, the number of equipment in A and B classes remains almost the same, especially for the A level. This last implication may be addressed the lack of women workforce in heavy industry sector.

8. Discussions

The two scenarios analyzed in Section 6 may confirm *P2* and *P3*. In particular, the results of the first scenario empirically support *P2*. The exclusion of social drivers implies a lower criticality generally assigned to equipment. If the social driver is neglected, we obtain a lower number of components within A and B classes. A summary of the overall results is provided in Table VII.

Class	With social driver (% components)	Without social driver (% components)
A	8.9	7.8
B	44.4	42.2
C	46.7	50.0

Table VII.
Criticality class assignment – comparison

With reference to the results obtained from the two models of this scenario, it is worth observing that about 3 percent of equipment that is classified in B class by the reduced model, is now in the A class, and about 7 percent of the equipment within C class is now in B class. On the other hand, for the present data set, no equipment has reduced its criticality. This clearly depends on the particular context and the relative weights of drivers indicated in its AHP matrixes. All in all, an increase of criticality is evident even if "people" is a driver with less importance than "environment" and "structures" (see Table III).

Then, the results are similar concerning maintenance policy selection, i.e. only some variations occur. In this context, for the present test case, the extended model can be seen as a refinement of the reduced model, leading to a limited shift in maintenance policies, toward preventive or condition-based/predictive ones. This may be addressed mainly to the plant in which we implemented the AR, its sector and managerial policies. In general, in heavy industries the presence of women or young workers is very low, as in this case. Moreover, as stated in Section 5, environmental compulsory norms shift the attention of firms toward environmental aspects, neglecting social ones. These considerations may justify the low variations in maintenance policies. In addition, for the test case, it is worth mentioning that the percentage of women/young workers is about 5 percent with respect to the maintenance staff, thus confirming the above considerations for heavy industries. On the other hand, more than young workers or women, a great percentage of the workforce conducting maintenance operations is of advanced age, with many related advantages but also some hidden risks. Age should therefore play an important role in maintenance, contributing to a different criticality for a certain equipment. Hence, although SA 8000 does not take into account the age factor, this is emphasized by adding it as an additional driver of maintainability (as in AHP model, Figure 1). As for heavy industrial contexts, and maintenance operations as well, scenarios characterized by aged employees can be expected to be more common than those characterized by high presence of women or young workers, thus requiring the same attention. Under this perspective, the results of the second scenario support *P3*. As can be argued by Figure 4, the age of maintenance workers clearly affects the criticality results, thus leading to increase criticality classes. It is also fair to say that the criticality analysis is slightly affected by gender factor, because, as shown in Figure 4, the amount of C-class equipment may be reduced in favor of B-class equipment, i.e. time-based preventive maintenance policy.

As a whole, the paper is intended to make both managers and workforce aware of secondary aspects that are sometimes neither compulsory, nor included in any norms or strictly relative to finance and productivity, as stated in *P1*. The results of both scenarios underline how a secondary aspect, like the social one, generates a different criticality for a certain item of equipment. Albeit the present work was developed within maintenance sector, *P1* can be extended to all industrial activities, including production and logistics. It can contribute to better working conditions, also leading to an improvement in well-regulated industrial aspects, e.g. safety. It is well known that compulsory norms and regulations about safety must be accompanied by a general understanding and awareness of active sharing and collaboration among the actors representing the workforce and managers. Generally speaking, in industries it is important to stimulate other aspects than the economic and productivity ones, clearly representing the main goal of each manager, with the aim to create an active and proactive environment in relation to compulsory and non-compulsory issues.

9. Conclusions

The present work has been focussed on the definition of a criticality ranking model-based additional features like of workers' gender and age. The approach has been conceived by the application of a fuzzy logic structure to front uncertainties deriving from environmental and social dimensions criteria. Then, fuzzy logic is combined with the AHP method, well known for its ability to support MCDM problems using tables and interviews. The combination of these two methods resulted in the possibility to evaluate alternative criticality ranks by considering the impact on workers' health and safety; and environment; and age and gender factors, which are usually neglected in current FMEA analysis. The AR proved the effects resulting from the consideration of either gender and age factors and then for; gender factor considered as stand alone. By benchmarking such different scenarios with the baseline, where age and gender are not considered, the action research gave the possibility to evaluate the impact of social drivers on the criticality assignment procedure for each component of the plant. A gap in IS has also been highlighted in relation to the consideration of age as a relevant factor for driving decision making, especially in heavy industries, as in the industrial case of this work.

A possible extension of this work may be focussing on maintenance costs under social and safety perspective. The method developed herein should be extended by further study of maintenance planning decisions subject to budget constraints. Moreover, it would be worth evaluating the effect of adopting more proactive maintenance policies aimed at improving plant maintainability. This last consideration can be intended as a limit of the presented approach. It is mainly based on what emerged during the test case with aged workforce, and the relative need to prevent and/or protect people from hidden safety risks.

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