Addressing the maintenance strategy selection issue in the industrial field: A literature review

Raffaele Abbate[a)], Maria Antonietta Turino[a)], Mario Caterino[b)], Marcello Fera[a)] and Roberto Macchiaroli[a)]

a. Department of Engineering, University of Campania Luigi Vanvitelli, via Roma 29, 81031, Aversa, CE, Italy

b. Department of Industrial Engineering, University of Salerno, Fisciano 81024, Italy

Abstract: Maintenance is a core aspect of any manufacturing company as it keeps production assets in good condition ensuring that they can perform at their nominal level. Good management of maintenance leads to economic, environmental, and social benefits. Several maintenance strategies have been developed over the years and the identification of the most appropriate one for an equipment represents a multi-objective problem since the needs of different stakeholders should be considered. The paper aims to contribute to this topic by investigating the literature to assess the maintenance strategies to use in industrial applications. The focus is on the identification of the most used decision support systems (DSS) ad their criteria for the maintenance strategy selection based on the needs of the industrial stakeholders. For such a purpose, a systematic literature review (SLR) has been conducted. Results show that the Multi-Criteria Decision Methods (MCDM) are the most used DSS and cost and safety are always the most important criteria leading towards the final decision.

Keywords: maintenance strategy selection, decision support systems, multi criteria decision methods

I. INTRODUCTION

Maintenance has critical importance for industries because of the direct and indirect costs that equipment without an appropriate maintenance strategy may represent. The right choice of maintenance strategy could lead to economic, social and environmental benefits (Carnero Moya, 2004). As the literature on this topic has widely demonstrated, maintenance management, often consisting of the correct choice of appropriate maintenance strategies, may represent a very complex task because it must consider different and, often, contrasting interests, such as the minimisation of the equipment breakdown for failures and the maximisation of the production rate (Murthy et al., 2002), or the minimisation of both economic and environmental impact (Fera et al., 2020). Over the years, several maintenance strategies have been introduced to improve management performance and increase the reliability and safety of production systems (Abbate et al., 2022). However, the choice of the most appropriate maintenance strategy can be represented as a multi-objective problem because the needs of different stakeholders must be considered and each equipment has own attributes and characteristics. Therefore, the best maintenance strategy cannot be determined univocally, but it depends on the specific case addressed (Wang et al., 2007). A way to facilitate the maintenance strategy selection is represented by the use of Decision Support Systems (DSS).

The use of a DSS consists in exploiting computer technology solutions to enhance and accelerate the decision-making process on a specific subject. According to Fitzgerald (Fitzgerald, 2002), the decision-making process involves three main phases: 1) the definition of the objective; 2) the identification of the alternatives; 3) the evaluation of the alternatives. Among these phases a DSS should be used for (Eom and Kim, 2006): i) supporting the decision makers, rather than replacing them; ii) exploiting data about the application domain; iii) using data analysis techniques to identify useful relationships among them; iv) evaluating the effect of each alternative against some defined criteria that consider the different objectives of the stakeholders. Hence, the DSSs offer a systematic approach to take a decision when different aspects impact the decision. DSSs have been widely used for maintenance purposes, such as for task prioritisation (Li and Ni, 2009), for health monitoring (Dey, 2004) and many other topics (Bousdekis et al., 2021). The use of DSSs may represent a feasible and effective way also in the case of the maintenance strategy selection, as recently demonstrated by Mostafa and Fahmy (Mostafa and Fahmy, 2020), who used a multi-criteria decision method for selecting the most

appropriate maintenance strategy in a natural gas processing plant, and Darestani et al. (Avakh Darestani et al., 2020), who combined two multi-criteria decision methods to create a DSS for maintenance strategy selection in a paper industry.
The aim of this paper is to contribute to the current literature by analysing the existing research on the topic of maintenance strategy selection conducted by means of DSSs. Through a Systematic Literature Review (SLR), this research wants to identify how the DSSs are used for the maintenance strategy selection, what are the most used DSSs and the principal criteria employed by the decision makers (based on the stakeholders needs).

II. METHODOLOGY

In this section, the main steps conducted to carry out the SLR will be described. Several sub-sections have been created to illustrate the steps followed to respond to the following research question (RQ):

- RQ1) How DSSs are currently used to support the identification of the most appropriate maintenance strategy selection?

A. *Identification of research databases and keyword definition*

Two scientific databases were used for the purpose of the paper, i.e., "Scopus" and "Web Of Science". Three groups of keywords were used to create the research string, namely topic, task and tool. The topic group defined the topic of the research. It includes the keywords: *Maintenance*, *Maintenance Strategy Selection* and *MSS*. The task group defined the purpose of the scientific publications. The following keywords were considered: *Decision Making*, *Selection*, *Decision*, and *Policy*. Finally, the tool group included the keywords *Decision Support Tool* and *DSS, i.e.* specified the tools used to support the achievements of the tasks. All the keywords were combined in the following research string: TITLE (maintenance AND (dss OR "decision support system" OR "decision-making" OR selection OR policy)) AND ABS ("maintenance strategy selection" OR mss OR dss OR "decision support system" OR (maintenance AND (selection OR decision OR policy))) AND AUTHKEY ("maintenance strateg*" OR decision making" OR "maintenance decision making" OR "maintenance strategy selection" OR "maintenance policy").

B. *Literature search and paper selection*

The relevant papers were identified through a two-phase screening process and four inclusion criteria. In the first phase, the relevant papers were identified by reading the title and the abstract, while the full reading of the papers allowed to identify the very relevant papers and extract the needed information. Four inclusion criteria were used to select papers: IC1) *only papers written in English*; IC2) *only journal and conference papers*; IC3) *papers dealing with the maintenance decision making in industrial applications.* This criterion was used to guarantee the homogeneity of the evaluation criteria used to evaluate the fitness of each alternative; IC4) *paper using a systematic approach to identify the most appropriate maintenance strategy.* This criterion aims to include all the key elements of a DSS (objective, alternatives definition and alternatives evaluation). Once the relevant papers were identified, the knowledge was extracted to identify the most relevant needs of the stakeholders that impact the identification of the most appropriate maintenance strategy and how the fitness of each maintenance strategy is evaluated against each need, as shown in Figure 1.

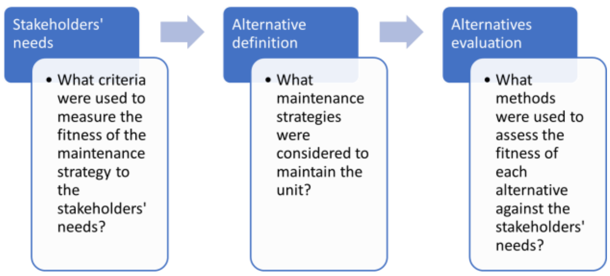

Figure 1. Information extraction process for the relevant papers

III. RESULTS

The search was run on 15 August 2022. The literature review process is shown in Figure 2. 610 publications were identified across the two scientific databases. The scanning for duplicates outlined 182 common publications between the two databases. The analysis of the number of publications over the years highlighted that 77% of publications have been published since 2012, therefore the authors decided to consider only the publications published since that year. Then, 20 papers were excluded due to IC1 and IC2, thus 308 were selected for the two-phase scanning process. In both phases, the identification of the relevant papers was led by IC3 and IC4. Indeed, 94 papers were excluded by IC3 since they were not related to the industrial field. Furthermore, a small number of papers were excluded because the focus was not coherent with the RQ. Thus, the remaining 214 papers were examined and, among them, 40 papers were selected as eligible for the purpose of this research. The 214 papers addressed several types of maintenance decisions grouped in several areas (Ruschel et al., 2017). The groups were: Maintenance planning (MD1), Maintenance strategy selection (MD2), Process monitoring analysis (MD3), Machine health prognosis (MD4), System and component degradation (MD5), Joint optimisation (MD6), Multi-level and Multi-state system integration and optimisation (MD7), Inspection and Maintenance Intervals (MD8). In this review, only the papers belonging to the MD2 area were analysed. Among them, only the papers using a systematic approach coherent with the extraction strategy depicted in Figure 1 were selected.

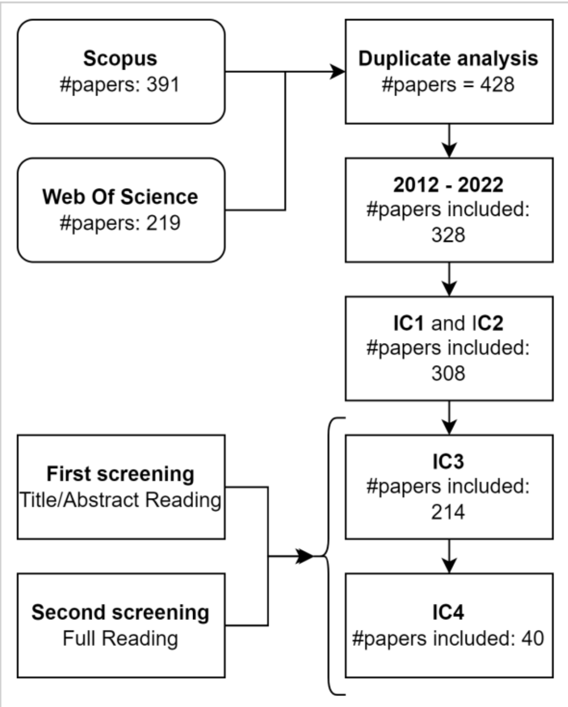

Figure 2. Literature review process

In the following, each area is briefly described to let the reader understand the motivation for including only MD2. MD1 developed models to assist decision-makers in the choice of the maintenance action to take once the maintenance strategy has been decided, e.g., replace, repair, do maintenance, do not maintenance, schedule maintenance. Papers in MD2 aim to identify the most appropriate maintenance strategy based on the stakeholders' needs and the unit's characteristics. MD3 includes papers that exploit the outcomes of the monitoring system to decide on the maintenance actions to take. Similarly, MD4 uses diagnostic and prognostic algorithms to predict the health status of the monitored unit to schedule maintenance activities. MD5 is mainly focused on the modelling of the degradation phenomena of the system and their impact on the scheduling of maintenance activities. MD6 aims to integrate maintenance and production plans developing optimisation models that consider both aspects. MD7 deals with the modelling of multi-level systems composed of several components and groups them for maintenance activities. Also, papers focused on the modelling of multi-state systems are included in this area. Finally, MD8 is focused on the development of methods and models to optimise the intervals between two inspections according to several boundary conditions. Figure 3 shows the trend over the years of the papers belonging to MD2 area (blue bars), the papers belonging to the other seven areas (grey bars) and the trend of the relevant papers (orange bars).

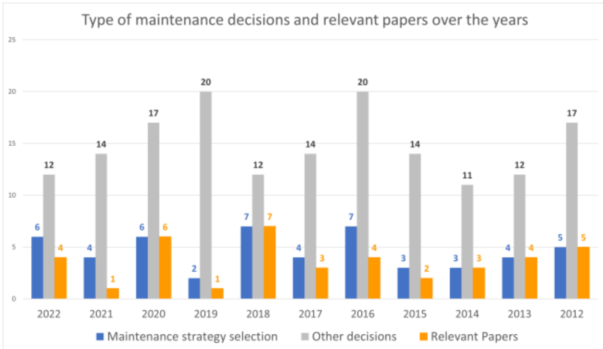

Figure 3. Trend over the years of the papers on the maintenance decisions distinguishing maintenance strategy selection, other decisions and relevant papers

A. *Results overview*

40 papers used a systematic approach to identify the most appropriate maintenance strategy, i.e., those addressing i) the concurrent needs of the stakeholders; ii) the criteria used to measure the fitness of each maintenance strategy related to the stakeholders' needs, and iii) the methods used to assess this fitness. These aspects are described and discussed in the following sections. The 40 papers are reported in the table available at the following link:https://drive.google.com/file/d/1O1mED2YPy-ZIp5_AvCyCRtHd0qZE4YXp/view?usp=sharing For each paper, the application field, the maintenance strategies, the criteria and the decision support methods are reported.

B. *Stakeholders' needs and criteria*

As highlighted in the introduction section, different stakeholders often have competing objectives and needs, whose accomplishment makes complex the decision-making process on the most appropriate maintenance strategy. The decision-making process is carried out through several criteria to measure the fitness of each maintenance strategy against each need. Twenty-five criteria were identified in the analysed papers, and they were split in five macro-area, namely: *Cost*, *Feasibility*, *Reliability*, *Added value* and *Safety*. The **cost area** includes six sub-criteria aiming to measure the economic impacts of the maintenance strategy and involves both investment and management costs. Investment costs are related to the purchase of hardware (C1), software (C2) platforms and training sessions for workers (C3). Management costs are related to the workers' hourly pay (C4), purchase of spare parts (C5) and energy consumption (C6). The **feasibility area** embraces seven sub-criteria aiming to evaluate how far is the maintenance strategy from the current state of the company in terms of mindset, technological level and skills. The sub-criteria included in this area aim to evaluate the maintenance strategy against the workers' skill (F1), workers' (F2) and managers' (F3) acceptance, technological readiness level (F4) (e.g., data availability, access to new technologies), flexibility (F5) (e.g., the ability of a manufacturing system to make quick modifications, fault tolerance) and maintenance load (F6) (expressed as the ratio between maintenance resources and resources to be maintained). Also, the security aspects (F7) of the software and the data are considered in this area. The **reliability area** aims to collect information about the reliability aspects of the unit to maintain. Thus, two sub-criteria are included in this area, the Mean Time Between Failure (MTBF) (R1) and the Mean Time To Repair (MTTR) (R2). The **added value area** aims to measure how the maintenance strategy contributes to the achievement of the company's goals. This area includes six sub-criteria to measure the impact of the maintenance strategy in the reduction of the inventory costs (AD1), in the increase of the quality of products (AD2), in the enhancement of the fault detection (AD3), in the increase of the availability (AD4) (i.e., downtime reduction) and in the increase of the efficiency of the system (AD5). In addition, the impact on the company's profit (AD6) is also considered. Finally, the **safety area** includes four sub-criteria, aiming to assess the impact of the maintenance strategy against the safety of the machines (S1), workers (S2) and workplace (S3). Furthermore, the environmental impact (S4) belongs to this area. Figure 4 provides an overview of the twenty-five criteria organised per macro area and sorted per number of citations.

For the sake of completeness, also the risk factor was considered by (Shafiee et al., 2019) and (Farajiparvar and Mayorga, 2018) for the maintenance strategy selection process. It was considered through two indexes, the Risk Priority Number (RPN) and Cost Priority Number (CPN). They were evaluated by means of the Failure Modes and Effects Analysis (FMEA) considering three dimensions, i.e., the occurrence of the fault, its severity and detectability.

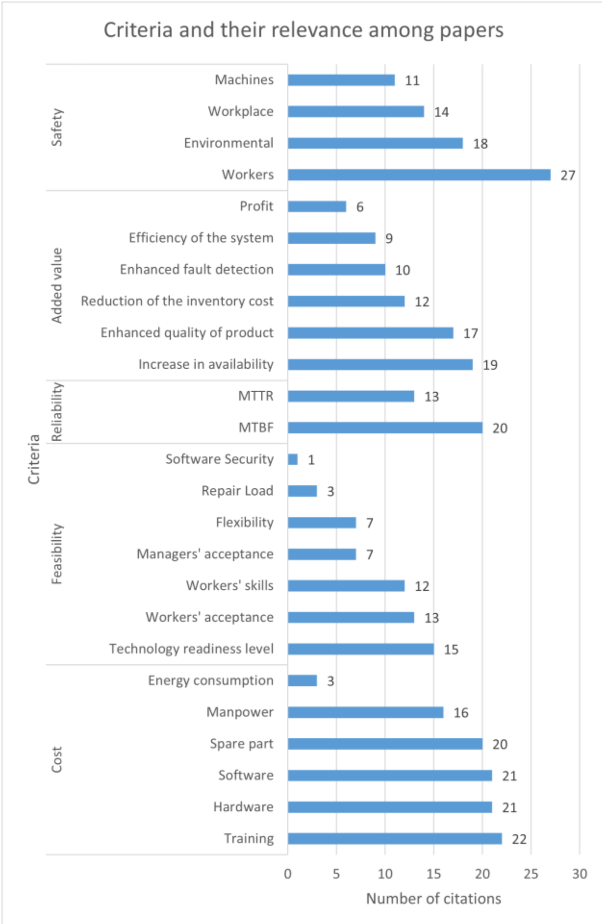

Figure 4. The twenty-five criteria organised per macro-area and sorted by number of citations

C. *Alternatives definition*

Several maintenance strategies were identified as alternatives in the relevant papers. Figure 5 shows an overview of the cited maintenance strategies and their relevance among the 40 analysed papers. The most considered maintenance strategies are Time-Based (TBM), Corrective maintenance (CM) and Condition-Based (CBM). Following, in descending order of citations there are Predictive

Maintenance (PdM), Reliability Centered maintenance (RCM), Total Productive maintenance (TPM), Design-Out-Maintenance (DOM), Autonomous maintenance (AM), Opportunistic maintenance (OM) and Total Quality maintenance (TQM).

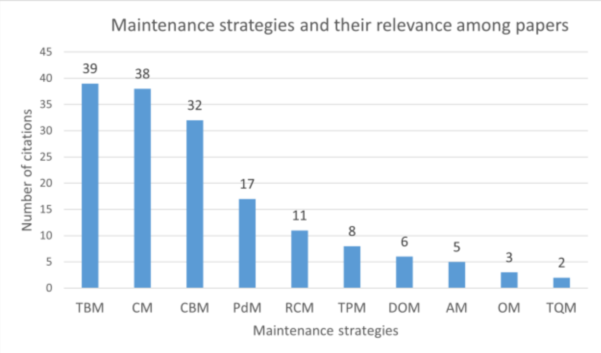

Figure 5. Maintenance strategies considered as alternatives in the selected papers and their number of citations

D. Alternatives evaluation

In this section, the methods used in the relevant papers to assess the fitness of each alternative (maintenance strategy) against the stakeholders' needs are discussed. The methods are organised in three macro categories (Ding and Kamaruddin, 2014a): Multi-Criteria Decision Making (MCDM) based methods, Graphical based methods and Heuristic based methods. The **MCDM methods** offer a systematic approach to evaluate several alternatives against different criteria, usually competitive, providing a ranking of the alternatives. In this category, the most used methods are the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution), AHP (Analytic Hierarchy Process), VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje) and ANP (Analytic Network Process). Others, less used, are: FAD (Fuzzy Axiomatic Design), GRA (Grey Relational Analysis), COPRAS (COmplex PRoportional ASsessment) and IVF (Interval Valued Fuzzy Numbers). Often, these methods are used in combination or are improved by using Fuzzy approaches or simulation tools like Monte Carlo analysis. For example, a Monte Carlo simulation was used to reduce the uncertainties in the experts' judgment on the maintenance strategies against the criteria in (Foroozesh et al., 2020). In (Kirubakaran and Ilangkumaran, 2015) three MCDMs were used to rank the maintenance strategies against the criteria, i.e., AHP was used to set the weights of the criteria while a combination of GRA and TOPSIS was used to rank the alternatives. An enhanced AHP approach was used in (Ge et al., 2017) by combining the Logarithmic Fuzzy Preference Programming (LFPP) with the AHP to introduce multiplicative constraints and deviation variables. The **graphical based methods** use a graph or figure to find the optimal maintenance strategy according to predetermined criteria (Ding and Kamaruddin, 2014). The Decision Making Grid (DMG) belongs to this category since it aims to plot the assets on two separate dimensions, usually downtime and failure frequency. Different levels of the two dimensions are defined and the best maintenance strategy for each couple of them is identified. In particular, in the papers using DMG, MTBF and MTTR were considered as the two dimensions (Seecharan et al., 2018; Shahin et al., 2018, Shahin et al., 2013). In this category, also two studies that developed an Abacus by means of mathematical expressions to identify the appropriate maintenance strategy are included. In (Faccio et al., 2014) the most appropriate maintenance strategy is identified by entering in the Abacus with the unit expect cost of the maintenance strategies, the Weibull parameters and the cost of the maintenance activities of the competing strategies. The **heuristic methods** make use of logic, experience and knowledge derived from observation to build a set of rules to guide the decision-making process (Tersine, 1985). Both studies using this method Lopez and Kolios, 2022) developed a maintenance Decision Tree (DT) to identify the most appropriate maintenance strategy by answering several questions and narrowing in such a way the applicable maintenance strategy.

IV. DISCUSSION

The literature review highlighted twenty-five criteria used to guide the selection of the most appropriate maintenance strategy that both reduces the failure's impacts and meets the stakeholders' needs. The investment criteria (hardware, software and training) are among the most considered ones, highlighting that companies are often concerned about the investment related to the implementation of new maintenance strategies, especially when these require the use of new technologies. This is also reflected in the feasibility macro-area, where the most considered criteria are the technology readiness level, the workers' acceptance and the workers' skills. These criteria aim to measure how far is the company from implementing the maintenance strategy and they are related to the investment criteria, which translates in cost such distance. Looking at the added value macro-area, it can be noted that the highest expectations of companies for the implementation of a new maintenance strategy rely on increasing the availability of their units and the quality of their products. In the analysis performed, also the safety dimensions arose among the most considered by the companies, addressing it through the workers' safety and the environmental aspect. Finally, the MTBF is highly considered to assess the importance of a unit toward the achievement of the companies' goals due to its inherent link with its availability.

Many of the findings analysed before are reflected in Figure 6, which shows the selected maintenance strategy against the most important aspect of the company. 18 out of 40 relevant papers provided both the ranking of the maintenance strategies and the importance of the criteria according to the expert's judgment. Thus, these two results were exploited to investigate the existence of a relationship among the four suggested maintenance strategies, namely the CBM, TBM, PdM and TPM and the five macro-areas of criteria identified. As it can be noted in Figure 6, all the maintenance strategies were judged as capable to improve the safety aspects, even if the PdM has greater safety potentials due to its ability to detect and predict the behaviour of the failure conditions over time, thus avoiding its occurrence. Furthermore, the results confirm that the diagnosis and prognosis abilities of the CBM and PdM could bring added value to the company and increase reliability. On the other hand, the cost appears as a limit towards their adoption. TBM is suggested when the cost is a constraint for the company. This last aspect confirms what emerged from the analysis of the criteria, which highlighted that the investment criteria are highly considered in the maintenance strategy selection process.

Figure 6. Suggested maintenance strategy according to the most important criteria

Finally, TPM was considered the most feasible against the other four maintenance strategies capable to improve the reliability of the equipment relying on the workers' skills and acceptance.

The literature review allowed the authors to outline a common framework, shown in Figure 7, in which there are two main actors involved in the maintenance strategy selection process, i.e., the stakeholders and the unit to be maintained. The identified criteria are further grouped together based on how they influence the selection process according to the two actors.

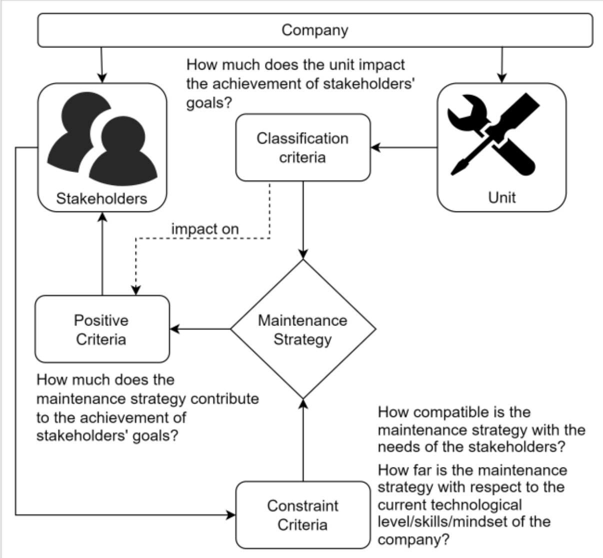

Figure 7. Common framework for maintenance strategy selection

Three groups are considered: *Constraint criteria*, *Positive criteria* and *Classification criteria*. The **constraint criteria** include cost and feasibility. They are constraints since they could be an obstacle for the company in implementing some kind of maintenance strategy, e.g., all the preventive maintenance strategies based on the acquisition and analysis of data could require a huge investment. Or even, the maintenance strategies that require deep involvement of the workers, such as TPM and AM could require a high level of worker's skills. Therefore, in this group, all the criteria representing a constraint for the company should be included. The **positive criteria** include the added value and safety criteria and they aim to measure the positive impact of the maintenance strategy towards the achievement of the company's goals. It is worth noting that the safety criteria could be considered also as constraint criteria in relation to the safety regulations of the country in which the company operates. Nevertheless, in this study, they are considered as positive criteria since the analysed case studies investigate how the different maintenance strategies could enhance the safety aspects. Finally, the **classification criteria** aim to evaluate how the failure of the unit impacts the achievement of the company's goal through the assessment of the reliability macro-area criteria and risk parameters such as RPN and CPN.

V. CONCLUSION

This paper conducted an SLR on the theme of DSSs used in industrial environments for maintenance strategy selection, often considering competing objectives. 40 papers were identified as relevant. Their analysis brought to conclude that 3 models are used as DSSs, i.e. MCDM models, graphical based models and heuristic methods, often using 25 main criteria. The result allows to conclude that, although CBM and PdM are the best strategies for increasing safety and the added value of the production processes, they are also the less cost-effective (considering the implementation) and the most difficult to implement. In this sense, TBM and CM seem to be still preferred for the easiness of implementation and the reduced costs. Thus, this represents an open issue that needs to be addressed in future research in this field.

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