Avenues for future research on predictive maintenance purposes in terms of risk minimization

Rim Louhichi, Mohamed Sallak, Jacques Pelletan

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Rim LOUHICHI

Université de Technologie de Compiègne, CNRS, Heudiasyc (Heuristics and Diagnosis of Complex Systems), CS 60 319 - 60 203 Compiègne Cedex . E-mail: rim.louhichi@hds.utc.fr

Mohamed SALLAK

Université de Technologie de Compiègne, CNRS, Heudiasyc (Heuristics and Diagnosis of Complex Systems), CS 60 319 - 60 203 Compiègne Cedex. E-mail: mohamed.sallak@hds.utc.fr

Jacques PELLETAN

Université Paris 8 et Institut Louis Bachelier, 28 Place de la Bourse, 75002 Paris, France. E-mail: jacques.pelletan@dauphine.fr

Risk is inherent in the very concept of maintenance as minimizing the risk of failure of an equipment is why we perform maintenance. The concept of risk-based maintenance has emerged as a tool for maintenance planning and decision making to reduce the probability of failure of equipment and the consequences of failure. In this paper, we study the purposes of predictive maintenance and we give an original classification of risk-based maintenance methodologies in literature according to criteria. These criteria of classification include the input data, the structure of the risk minimization process, the decision variables, the methodology adopted, the output data, the application field and the factors that impact the quality of risk analysis. This review shows that the choice of methodologies, input data and decision variables are highly impacted by the model of the risk minimization process adopted as well as the context and the application fields.

Keywords: maintenance, predictive maintenance, purposes, risk analysis, risk minimization, classification, criteria

1. Introduction

Maintenance is *"the combination of all technical, administrative and managerial actions of an item intended to retain it in, or restore it to, a state in which it can perform its required function"* [1]. Maintenance has a strategic role in maintaining the competitiveness of a company through reducing product/service cost. In fact, according to [2], maintenance cost accounts for 15% to 70% of the total production cost. Therefore, it is primordial for companies to choose the optimal maintenance strategy that allows them to reach competitive market prices.
The emergence of new technologies such as artificial intelligence and internet of things has allowed the widespread application of predictive maintenance. Predictive maintenance is a maintenance strategy that involves condition monitoring, fault diagnosis, fault prognosis and maintenance plan [3]. Condition monitoring, fault diagnosis and prognosis can be achieved thanks to sensing technologies that are usually combined with algorithms that use artificial intelligence. According to [4], three fundamental issues should be considered while working on predictive maintenance: the architecture of predictive maintenance able to embrace these emerging technologies, the purposes of predictive maintenance that are sometimes conflictual and the approaches used for fault diagnosis and prognosis.
In this paper, we focus on the second fundamental problem which is the purposes of predictive maintenance. First, we identify the diverse purposes of predictive maintenance according to literature. We then focus on risk minimization as a purpose of predictive maintenance. This choice is justified by the fact that risk is a large concept that may include the other purposes of predictive maintenance which are cost minimization and reliability/availability maximization.
We provide in this paper an original classification of literature works on risk-based maintenance methodologies according to predetermined criteria and finally, we provide some conclusions.

2. Predictive maintenance purposes

Although predictive maintenance has been widely defined in literature, we prefer as well refer to the standard definition of predictive maintenance as given in the European norm EN13-306:
"Condition-based maintenance carried-out fol-

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lowing a forecast derived from the analysis and evaluation of the significant parameters of the degradation of the item" [1].
Predictive maintenance requires the use of condition monitoring devices (sensors) and it is usually a challenging task to analyze data, predict the failure of the system and make decision on when to perform maintenance [4]. The making decision process is conditioned by the purpose to attain from predictive maintenance.
In this paper, we describe briefly the purposes of predictive maintenance as described in literature review [4] and we study another purpose for predictive maintenance which is risk minimization.

2.1. *Cost minimization*

The maintenance strategy is based on minimizing a total cost function that includes generally the cost of corrective maintenance, the cost of predictive maintenance, the cost of inspection and the cost of loss of operating capacity of the system due to maintenance. The evaluation of the total cost uses data related to the system operation condition such as the reliability measure or the remaining useful life. The objective cost function may be the long-run expected cost rate, the expected cost rate or the total cost during a time cycle T (such as replacement cycle, planning horizon...). Usually, the cost minimization approach aims at determining the optimal predictive maintenance threshold and the inspection planning.

2.2. *Reliability/availability maximization*

The European norm EN13-306 defines reliability as:
"The ability of an item to perform a required function under given conditions for a given time interval" [1].
In reality, a system is composed of different components which are inter-dependant. A reliability model for complex system can be derived using the degradation process of each component and the dependency among them. The failure time can be approximated using simulation method. Predictive maintenance is then planned according to the predicted failure time.
Similarly, the availability, defined by the European norm EN13-306 as : *"ability of an item to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided"* [1], is heterogeneous within a complex system as each component has a different level of availability. Generic availability model can be constructed for different system architectures (series, parallel or series-parallel systems). The objective is to identify the best time for inspection and maintenance that maximize the availability of the whole complex system.

2.3. *Risk minimization*

According to [5], *"risk analysis is a technique for identifying, characterizing, quantifying and evaluating the loss from a failure event"*. Risk can be defined in a quantitative or qualitative way as the product of the probability of occurrence of a failure event and the severity of that event [5]. The classical approach for predictive maintenance based on risk analysis follows the next steps [5, 6]:

- Identification of failure events.
- Identification of causes of these failure events and their probability of occurrence. A way to evaluate the probability of occurrence of failure event is by adopting the fault tree analysis method.
- Evaluation of consequences of failure events.
- Risk assessment.
- Setting up acceptance risk criteria.
- Comparison of assessed risk with acceptance criteria.
- Maintenance scheduling to bring down unacceptable risk to the acceptable level of risk.

Sometimes, the risk assessment is translated in currency terms. Therefore, minimizing maintenance risks goes back to minimizing maintenance costs.

2.4. *Multi-objective optimization*

Usually, the predictive maintenance purposes are conflictual. For example, minimizing the total maintenance cost does not guarantee a high level of system availability. This is due to the fact that systems are usually heterogeneous and contain components with different degradation process and maintenance costs. The multi-objective optimization aims at identifying the decision variables that achieve the best trade-off between these different maintenance purposes. The optimal decision variables determine the policy of predictive maintenance [7, 8, 9, 10].
In appendix A, we provide an update of the literature review on predictive maintenance strategies developed by [4].

3. Risk minimization

The literature review on risk-based maintenance optimization methods shows that there are different criteria for classification [11]. These criteria include the methods of risk estimation, the type of input data required to carry risk analysis, the type of output data, the type of application and the factors affecting the quality of risk analysis [11, 12]. In this section, we give a description of each criteria. These criteria have served as a guideline throughout this work.

3.1. *Methodology for risk analysis in maintenance*

According to [11, 12], risk analysis can be quantitative, qualitative or semi-quantitative. The quantitative approaches attempt to give a numerical evaluation of the risk by estimating its frequency and consequence, while qualitative approaches give simple descriptions of accidents, their likelihood and consequences. The results in the later approaches are usually given in the form of risk matrix [13].
Risk analysis methodologies can be classified also into deterministic, probabilistic or a combination of deterministic and probabilistic approaches [11, 12]. Deterministic approaches suppose that the risk occurrence is certain while probabilistic approaches, as their name suggest, assume that the risk occurrence is probable [11, 12].
In [11], the author suggests a classification based on modules (units of the risk analysis process), where the techniques of risk-based maintenance are classified into techniques for :

- Hazard analysis
- Consequence estimation
- Likelihood estimation
- Risk estimation
- Risk acceptance
- Maintenance planning

According to [5], risk can be of different types:

- Risk of loss of system performance due to component/unit failure.
- Risk of financial loss due to potential damage of properties/assets following a failure event.
- Risk of human loss due for example to exposures to toxic chemicals.
- Risk of environmental loss due for example to release and dispersion in the atmosphere of toxic chemicals.

3.2. *Model of risk minimization process*

According to the considered system, the available input data and the objective to be attained, risk minimization can take two different types:

- Optimization of an objective function: in this case, we aim to minimize a risk under constraints. The decision variables are generally the maintenance/inspection planning [14, 15].
- Comparison of the evaluated risks with risk acceptance criteria: in this case, the decision variable is the risk that we evaluate and which is compared to risk acceptance criteria in order to identify the best time for maintenance [5, 16].

The model of the risk minimization process must be considered in the first step before the methodology for risk analysis.

3.3. *Decision variables*

Methodologies for risk analysis in maintenance differ in the decision variables used to plan maintenance. For example, in [14], the remaining useful life, defined as the expected interval of time the system is likely to operate before it falls down, is used as a decision variable to plan maintenance. In [15, 17], the maintenance time and the maximum length of time between two consecutive inspections that result in a minimum accepted risk are the decision variables of a mathematical optimization program while in [5], the classical risk evaluated as the product of consequence and likelihood of a failure scenario is used as a decision variable to plan maintenance.

3.4. *Input data and output data*

The input data required to carry risk analysis for maintenance can be classified into :

- quantitative : such as failure probability, equipment costs, and historical knowledge
- qualitative : such as expert opinion, description of equipment functioning and operating conditions, safety barriers...

We refer to the work of [12] for further details on input data needed for risk analysis in maintenance. We suggest in this paper another classification for input data according to the source of the input data. In fact, input data can be historical (accident records, historical database...) [16], expert knowledge [5] or inspection data coming from the process of system monitoring [14].
Similarly, the output data of risk-based maintenance approaches can be classified into two classes :

- qualitative data: such as recommendations based on expert opinions. The output results are less precise and adopted in case of lack of sufficient data to perform numerical evaluation of risks [11].
- quantitative data: such as index of risk level [11].

For further details on the output data of risk analysis in maintenance, we also refer to the work of [12].

3.5. *Type of application*

The literature review shows that there are two types of application for risk-based maintenance approaches:

- Industrial applications including mechanical, chemical and electrical fields [11, 12].
- Transportation of dangerous goods [11, 12].

3.6. *Factors affecting the quality of risk analysis in maintenance*

In [18], the author presents a comparative study based on three independent risk analyses performed on a hydro-power plant and identifies through this comparison the various factors that affect the quality of the risk analyses in maintenance. These factors are:

- Hazard identification and initial consequence analysis
- Risk estimation
- Results

This list is not exhaustive. We refer to the work of [14] for more details. Fig. 1 gives an overview of the different factors impacting the quality of risk analysis in maintenance.

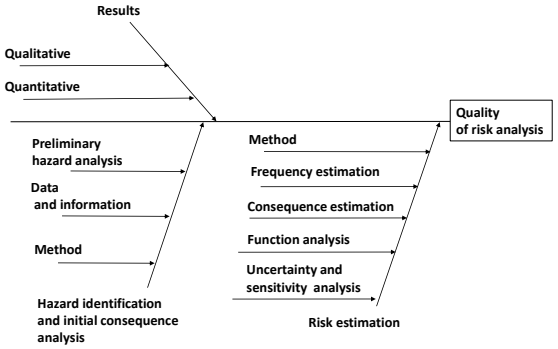

Fig. 1. Factors impacting the quality of risk analysis in maintenance [11, 18]

3.7. *Classification of risk-based maintenance methodologies*

In this section, we give a classification of papers on risk-based maintenance since 2000 following the classification criteria cited above.
In Fig.2, the sub-criteria that are proposed in this paper are framed in a rectangle. We mention that in Fig.2, the classification according to *"factors impacting the quality of risk analysis"* means that some of these factors are missing in the paper, which can impact the quality of the results.

3.8. *Discussion*

Following the classification shown in Fig.2, the above conclusions can be drawn :

- We identify in all the studied papers the presence of both qualitative input data (system description, failure event description,...) and quantitative input data (historical database, failure mode distribution...). The input data that are coming from historical database/records are generally accompanied with expert knowledge in order to transform this raw data into processable data [5, 13, 15, 27]. The input data coming from the inspection process do not necessarily require expert knowledge [14, 21, 24]. The inspection process is generally used in the scale of a unit [14, 21, 24]. The output of the inspection process is a parameter used later to evaluate the probability of occurrence of failure event. The parameter varies according to the studied system and its context of application [14, 21, 24, 26].
- The choice of the model for maintenance risk minimization determines the decision variables to adopt. The correspondence between the two typologies is shown in Fig.3. Fig.3 shows the differences between both typologies. It explains different approaches to perform maintenance risk assessment which can be a safety approach by comparing risks to acceptance criteria or an economic approach by minimizing a cost function. Both approaches are to be carried out in research on risk assessment in maintenance.
- Different methods to analyse failure scenarios, to estimate risk and to decide for maintenance/inspection planning are used according to the corresponding module of maintenance risk analysis. Some methods are based on expert opinion (brainstorming, analytical hierarchy process, technique for order of preference by similarity to ideal solution...) [23,33] while others are not (failure probability, availability model, ...) [16, 27]. Therefore, it is judicious to model the uncertainty on decision making through introducing fuzzy logic for example [29, 30, 31]. Otherwise, this may impact the quality of risk analysis [18].
- The type of risk varies according to the studied system and the context of application. However, we can always come back to an aggregated classification of risks into: financial (system performance loss [14, 25], loss of image [20, 28]), environmental (noise [32], explosion [32], fire [33]) and human risks (toxicity [21], human injury [21, 28]). This can also be translated in terms of monetary risks; for example, the cost of a human injury can be evaluated by the cost of compensation due to the employee.There is so much to be done in risk evaluation, mainly in human risk as human risk remains a crucial topic.
- The qualitative output data consists generally in an appreciation of risk level which does not guarantee an accurate maintenance planning [20, 21]. The time for maintenance is not determined mathematically. However, the results are given in the form of check-list on priority

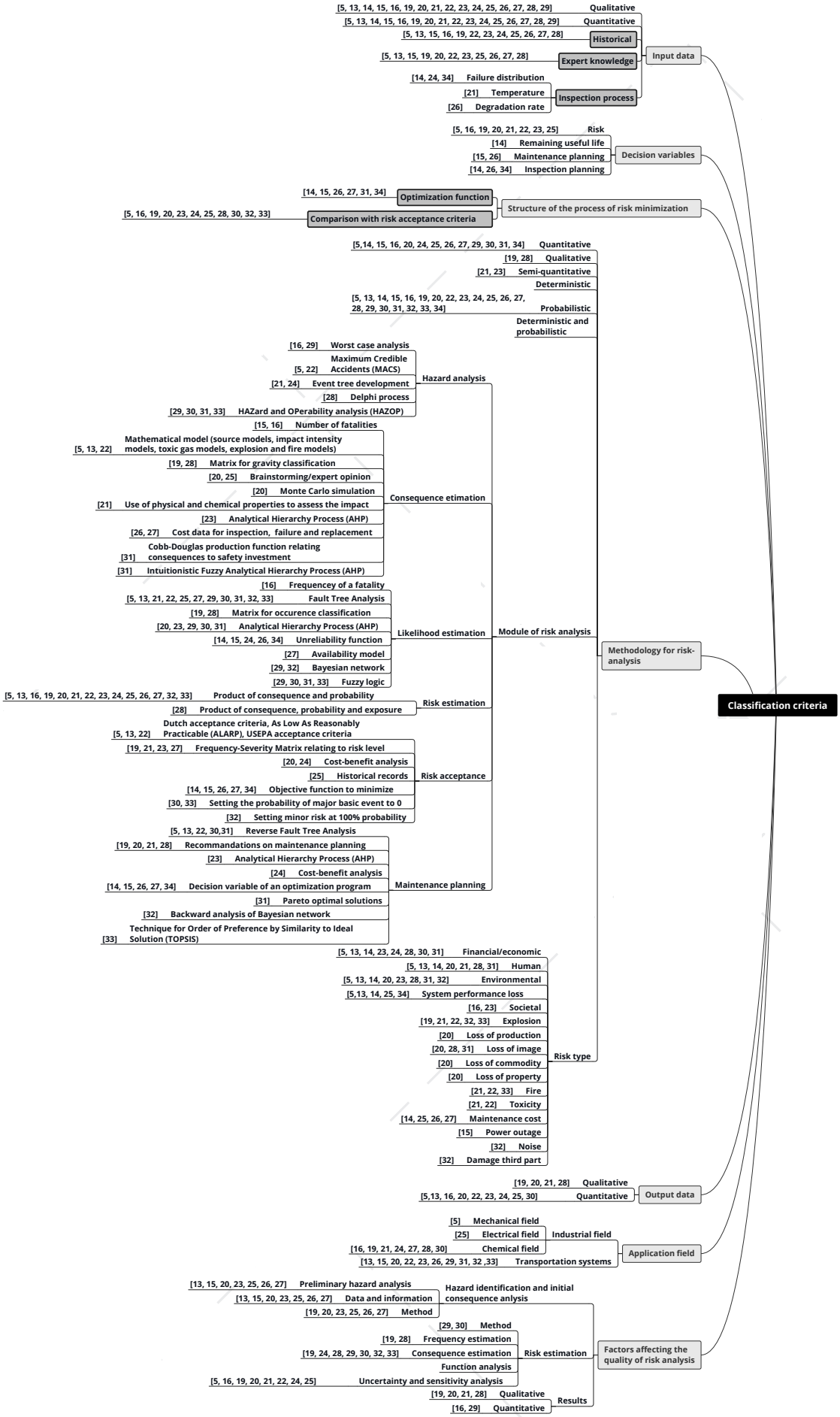

Fig. 2. Classification of risk-based maintenance methodologies according to criteria related to input/ output data, methodology used, type of application and factors impacting the quality of risk analysis

actions [20] or list of recommendations [21].

- The factors impacting the quality of risk analysis that are frequently missing in the studied papers are : hazard identification and initial consequence analysis [13, 15, 20], consequence estimation [29, 30, 32] and uncertainty/sensitivity analysis [5, 16, 19]. In some papers, it is on purpose to focus more on a risk analysis module than another [22]. In other papers, we carry only a qualitative analysis of risk which remain less accurate than quantitative analysis. Therefore, the results on maintenance planning are usually in the form of check-list on priority actions [20], list of recommendations [21] ...
- According to our study, the areas of application that stand out the most are the domain of chemical industry [24, 25, 27] and transportation of dangerous goods [20, 22, 23]. This can be explained by the fact that systems in these domains require a high level of reliability : a failure on these systems may have irreversible damage on human health and environment.
- The uncertainty on input data and the attitude of the decision maker to risk make the process of decision making a complex task. In fact, the work of [35] has demonstrated the impact of cognitive knowledge on risk assessment, while in [36], it has been demonstrated that human emotions play a major role in rational decision-making. Unfortunately, these aspects have not been well studied in previous papers on maintenance risk assessment.
- The quantitative implementation of a risk-analysis approach depends on the sector, the strategy adopted by a company (whether to enhance security or economize money), the type of risks concerned by the sector, the available data that a company dispose and other factors. A lot of work needs to be done to identify the best practices in risk analysis adapted to company's context and needs. There is therefore no better methodology to carry risk analysis in maintenance.

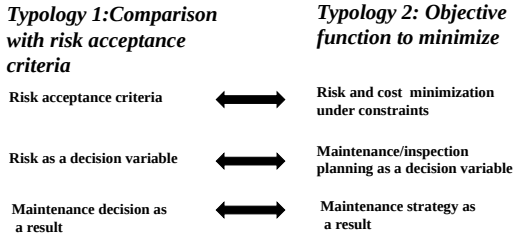

Fig. 3. Proposed correspondence between the two typologies of risk-based maintenance

4. Conclusion

In this paper, we define the concept of predictive maintenance and its purposes according to literature. We point a major purpose of predictive maintenance that has not been tackled in [4] which is risk minimization. The literature review on risk-based maintenance methodologies shows that there are two main typologies of risk-based maintenance methodologies : in the first typology, we evaluate the level of risk and compare it with risk acceptance criteria [5, 16, 19], while in the second typology, we minimize an objective function (risk) and identify the decision variables that consist usually in the maintenance/inspection planning [14,15, 26, 34]. We have also identified different types of risks and different techniques to estimate risks and plan maintenance accordingly. The classification presented in this paper serves as a guide for experts to easily identify the best tools and techniques to carry risk analysis. There is no better technique to carry risk analysis: we leave the choice of the technique to the skill of the expert.
This classification can always be improved by aggregating some criteria or by crossing criteria that can be intercepted or redundant. It is always possible to further detail the classification by introducing more advanced sub-criteria. Finally, we mention that it may be interesting to define, according to the area of application, a standard that defines the best practices and techniques to carry risk-based maintenance. Our proposed method of classification can be a preliminary step towards establishing this standard.

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References

1. Association Française de Normalisation (AFNOR), (2018). *Maintenance Terminology*.
2. Bevilacqua, M., and Braglia, M. (2000). *The analytic hierarchy process applied to maintenance strategy selection.* Reliability Engineering and System Safety, 70(1), 71-83
3. Wang, J., Zhang, L., Duan, L., and Gao, R. X. (2017). *A new paradigm of cloud-based predictive maintenance for intelligent manufacturing.* Journal of Intelligent Manufacturing, 28(5), 1125-1137.
4. Ran, Y., Zhou, X., Lin, P., Wen, Y., and Deng, R. (2019). *A Survey of Predictive Maintenance: Systems, Purposes and Approaches*. IEEE Communications Surveys and Tutorials.
5. Khan, F. I., and Haddara, M. M. (2003). *Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning.* Journal of Loss Prevention in the Process Industries, 16(6), 561-573.
6. Apeland, S., and Aven, T. (2000). *Risk based maintenance optimization: foundational is-*

sues. Reliability engineering and system safety, 67(3), 285-292.
7. Tian, Z., Lin, D., and Wu, B. (2012). *Condition based maintenance optimization considering multiple objectives.* Journal of Intelligent Manufacturing, 23(2), 333-340.
8. Xiang, Y., Coit, D. W., and Zhu, Z. (2016). *A Multi-objective Joint Burn-in and Imperfect Condition-based Maintenance Model for Degradation-based Heterogeneous Populations.* Quality and Reliability Engineering International, 32(8), 2739-2750.
9. Lin, L., Luo, B., and Zhong, S. (2018). *Multi-objective decision-making model based on CBM for an aircraft fleet with reliability constraint.* International Journal of Production Research, 56(14), 4831-4848.
10. Zhao, J., and Yang, L. (2018). *A bi-objective model for vessel emergency maintenance under a condition-based maintenance strategy.* Simulation, 94(7), 609-624.
11. Arunraj, N. S., and Maiti, J. (2007). *Risk-based maintenance—Techniques and applications*. Journal of hazardous materials, 142(3), 653-661.
12. Tixier, J., Dusserre, G., Salvi, O., and Gaston, D. (2002). *Review of 62 risk analysis methodologies of industrial plants.* Journal of Loss Prevention in the process industries, 15(4), 291-303.
13. Khan, F. I., and Haddara, M. R. (2004). *Risk-based maintenance of ethylene oxide production facilities.* Journal of hazardous materials, 108(3), 147-159.
14. Louhichi, R., Sallak, M., and Pelletan, J. (2019, June). *A cost model for predictive maintenance based on risk-assessment.* CIGI Qualita, Montreal, Canada.
15. Dehghani, N. L., Darestani, Y. M., and Shafieezadeh, A. (2020). *Optimal life-cycle resilience enhancement of aging power distribution systems: A MINLP-based preventive maintenance planning.* IEEE Access, 8, 22324-22334.
16. Hirst, I. L., and Carter, D. A. (2000). *A "worst case" methodology for risk assessment of major accident installations.* Process safety progress, 19(2), 78-85.
17. Khan, F. I., Haddara, M. M., and Bhattacharya, S. K. (2006). Risk-based integrity and inspection modeling (RBIIM) of process components/system. Risk Analysis: An International Journal, 26(1), 203-221.
18. Backlund, F., and Hannu, J. (2002). *Can we make maintenance decisions on risk analysis results?*. Journal of Quality in Maintenance Engineering.
19. Rogers, R. L. (2000) *Methodology for the Risk Assessment of Unit Operations and Equipment for Use in Potentially Explosive Atmospheres, The RASE Project: Explosive Atmosphere: Risk Assessment of Unit Operations and Equipment*, EU Project No: SMT4-CT97-2169.
20. Dey, P. K. (2001). A *risk-based model for inspection and maintenance of cross-country petroleum pipeline.* Journal of Quality in Maintenance Engineering.
21. Kao, C. S., and Hu, K. H. (2002). *Acrylic reactor runaway and explosion accident analysis.* Journal of Loss Prevention in the Process Industries, 15(3), 213-222.
22. Khan, F. I., and Abbasi, S. A. (2002). *A criterion for developing credible accident scenarios for risk assessment.* Journal of Loss Prevention in the Process Industries, 15(6), 467-475.
23. Dey, P. K., Ogunlana, S. O., and Naksuksakul, S. (2004). *Risk-based maintenance model for offshore oil and gas pipelines: a case study.* Journal of Quality in Maintenance Engineering.
24. Fujiyama, K., Nagai, S., Akikuni, Y., Fujiwara, T., Furuya, K., Matsumoto, S.,Takagi, K. and Kawabata, T. (2004). *Risk-based inspection and maintenance systems for steam turbines*. International Journal of Pressure Vessels and Piping, 81(10-11), 825-835.
25. Krishnasamy, L., Khan, F., and Haddara, M. (2005). *Development of a risk-based maintenance (RBM) strategy for a power-generating plant.* Journal of Loss Prevention in the process industries, 18(2), 69-81.
26. Khan, F. I., Haddara, M. M., and Bhattacharya, S. K. (2006). *Risk-based integrity and inspection modeling (RBIIM) of process components/system.* Risk Analysis: An International Journal, 26(1), 203-221.
27. Khan, F. I., Haddara, M., and Krishnasamy, L. (2008). *A new methodology for risk-based availability analysis.* IEEE Transactions on Reliability, 57(1), 103-112.
28. Bertolini, M., Bevilacqua, M., Ciarapica, F. E., and Giacchetta, G. (2009). *Development of risk-based inspection and maintenance procedures for an oil refinery.* Journal of Loss Prevention in the Process Industries, 22(2), 244-253.
29. Yazdi, M., and Kabir, S. (2017). *A fuzzy Bayesian network approach for risk analysis in process industries.* Process safety and environmental protection, 111, 507-519.
30. Yazdi, M., and Zarei, E. (2018). *Uncertainty handling in the safety risk analysis: an integrated approach based on fuzzy fault tree analysis.* Journal of failure analysis and prevention, 18(2), 392-404.
31. Yazdi, M., Nedjati, A., and Abbassi, R. (2019). *Fuzzy dynamic risk-based maintenance investment optimization for offshore process facilities.* Journal of Loss Prevention in the Process Industries, 57, 194-207.
32. Leoni, L., BahooToroody, A., De Carlo,

F., and Paltrinieri, N. (2019). *Developing a risk-based maintenance model for a Natural Gas Regulating and Metering Station using Bayesian Network.* Journal of Loss Prevention in the Process Industries, 57, 17-24.
33. Yazdi, M., Korhan, O., and Daneshvar, S. (2020). *Application of fuzzy fault tree analysis based on modified fuzzy AHP and fuzzy TOPSIS for fire and explosion in the process industry.* International journal of occupational safety and ergonomics, 26(2), 319-335.
34. Louhichi, R., Sallak, M., and Pelletan, J. (2020). A Maintenance Cost Optimization Approach: Application on a Mechanical Bearing System. International Journal of Mechanical Engineering and Robotics Research, 9(5).
35. Tversky, A., and Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. science, 185(4157), 1124-1131.
36. Jean-Pierre, C. (1983). "The neural man". Paris, Fayard.

Appendix A. Literature review of optimizing predictive maintenance strategy

The following table can be added to work of [4] in order to complete the literature review on optimizing predictive maintenance strategies:

Table 1. Continuation of the work of [4] on literature review on optimizing predictive maintenance strategies

Reference	**Objective function**	**Equipment**	**Solving methodologies**
[2]	Risk	Oil refinery	-
[11]	Risk	Heating Ventilation and air conditioning system	Heuristic
[13]	Multi-objective	Shear pump bearings	Physical programming approach
[15]	Multi-objective	Aircraft fleet	Two-models-fusion
[16]	Multi-objective	Manufactured components	Rosenbrock method
[19]	Risk	Ethylene oxide production facilities	Heuristic
[21]	Risk	Aging power systems	LINDO solver, Branch and Bound framework
[20, 40]	Risk cost	Generic industrial systems	Heuristic
[23]	Risk	Oil pipelines	Heuristic
[26]	Risk	Oil pipelines	-
[27]	Risk	Chemical installation (reactor)	-
[29]	Risk	Oil and gaz pipelines	-
[30]	Risk	Steam turbines	Heuristic