Orchestration of preventive maintenance interventions

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Abstract: **The paper has the objective of planning the preventive maintenance of a system subject to different failure modes. The preventive maintenance is planned by means of the maximization of the system reliability. The reliability of a system depends on many factors. One of these is the arrangement of the maintenance interventions in a specified time horizon and this is an aspect that has received low attention by literature. A reliability-centered maintenance optimization model is developed in the paper and the optimization can be tackled by means of two methods, according to the fact that the concept of joint replacement is introduced or not.**

Keywords: reliability; failure mode; preventive maintenance; maintenance scheduling

1. INTRODUCTION

The quantification of the performance of a system is of primary importance. The three main performance measures to characterize an equipment from the maintenance perspective are the so-called RAM parameters: Reliability, Availability and Maintainability (Nakagawa, 2005; Furlanetto and Garetti, 2006). The quantification of how long an equipment can operate without failure is made by means of the reliability, which is defined as the probability that the equipment will perform a required function under stated conditions for a stated period of time (Macchi et al. 2012a). When equipment is replaced upon failure or are preventively maintained, the focus is on the ratio at which equipment can operate, i.e. availability (Macchi et al. 2012b). Another important aspect is the ease and rapidity with which a system or equipment can be restored to operational status following a failure, i.e. maintainability. The three performance measures are closely related: if a system is very reliable, it is generally also highly available, while a system that is available may or may not be reliable, depending on maintainability. In fact, it is possible to achieve high availability also considering components that are not very reliable. In a system composed of many low reliable components, if the components are replaced quickly, the overall system can achieve a high availability. So the three parameters together are necessary to give a complete overview of the system performance, in order to deploy a competitive maintenance business model (Holgado et al. 2015).

It is important to keep reliability at high level when failure cost is high (e.g. spare parts replacement cost, damages cost, etc.) and when failures have dramatic consequences, where safety is of primary importance (e.g. in the case of airplanes, nuclear and chemical plants); on the other hand, availability is important when hidden costs are high (loss of production, service unavailability, etc.) (Furlanetto and Garetti 2006). In the former, maintenance costs have to be minimized while keeping the risks within strict limits and meeting satisfactory requirement.

The system reliability R_{sys} depends on many factors, the main ones are discussed hereafter.

R_{sys} depends on the reliabilities of the various equipment that suffer possible failure modes. It is thus possible to logically link the reliability to the single failure mode: R_i. The reliability of a generic failure mode i depends on the parameters used to describe its failure behaviour. If the failure behaviour is described by the Weibull distribution, three parameters have to be considered: the typical life α, the shape factor β and the time scale factor γ (Macchi et al. 2012a).

The system reliability depends on the number of interventions that are possible in the planning horizon. The planning horizon is the time window in which the maintenance must be planned. Generally speaking, the reliability of the system can be kept at high level with an elevated number of maintenance interventions.

The human factor influences the system reliability. Sometimes, the operators do not perform the maintenance intervention perfectly and, as a consequence, a partial (or even null) improvement of the reliability follows. The human factor is strictly related to the concept of imperfect maintenance, which can be applied to either preventive and corrective maintenance policies. The preventive maintenance interventions (PMs) can be categorized into three types: inspection only (the component is restored to its operating condition without any improvement on its reliability), low-level repair (it improves the state of the component in terms of reliability, but does not make it as-good-as-new) and high-level repair (it restores the system to an as-good-as-new condition) (Jardine, 2005; Doostparast et al., 2014). On the other hand, two types of corrective maintenance interventions (CMs) can be typically performed: minimal repair (the component is maintained in an as-bad-as-old state) and corrective replacement (the component is restored to an as-good-as-new condition) (Lie & Chun 1986; Tsai et al. 2001).

A last factor that influences the system reliability is the arrangement of the maintenance interventions in the planning horizon, i.e. the disposition of the interventions in the time window under consideration. Keeping the same number of interventions in the planning horizon, a proper disposition of the interventions can lead to higher system reliability: the disposition that maximize the reliability can be found. The

search of the best disposition of the interventions to maximize the reliability is herein defined as *orchestration*. This concept is not much treated in literature. This paper wants to contribute on the research about the impact of this novel factor on the system reliability.

The work focuses on a generic system and its failure modes that are assumed to be maintainable, independent and in a series-wise configuration (Fedele and Furlanetto, 2004). A failure mode is maintainable if the reliability can be improved by means of a maintenance action (Zequeira & Be 2006; Castro 2009; Lin et al. 2000). Two failure modes are independent if an intervention to face the first failure mode does not affect the other failure mode and vice versa (Zequeira & Be 2006).

In Section 2, an overview on the maintenance optimization models is given. A new maintenance reliability-based optimization model is presented in Section 3. The optimization can be developed by means of two different methods, according to the fact that the concept of joint replacement is introduced or not. Eventually, Section 4 provides conclusions on the proposed methods.

2. OVERVIEW ON MAINTENANCE OPTIMIZATION MODELS

A maintenance optimization model is a mathematical model in which both costs and benefits of maintenance are quantified and in which an optimum balance between both is obtained, while taking all kinds of constraints into account (Dekker 1996; Vasili et al. 2011). Many optimization models to plan maintenance are presented in literature but they are often very complicated, i.e. it is difficult to apply them in real industrial environments. On the other hand, there are methods (such as the Reliability Centered Maintenance - RCM) that are often too qualitative and, therefore, cannot be used as mathematical bases for quantitative optimization model (Zio 2009; Vatn et al. 1996; Lopez Campos et al. 2010). A need emerges: having a practical and user-friendly tool to plan the maintenance with, at the same time, a mathematical background to quantify numerically the performance and the effectiveness of the system under study.

According to the above mentioned literature background, the authors propose a classification between the methods used to plan the maintenance according to their objectives:

- *Cost-based approach*: the objective function is the minimization of the maintenance costs.
- *Availability-based approach*: the objective function is the minimization of downtimes (maximization of availability) or the minimization of maintenance costs while respecting constraints regarding the system availability.
- *Reliability-based approach*: the objective function is the maximization of the reliability of the system or the minimization of maintenance costs while respecting constraints regarding the system reliability.

An item is subject to sudden failure, and when failure occurs, the item has to be replaced. In order to reduce the number of failures, preventive replacements can be scheduled to occur at specified intervals. However, a balance is required between the amount of resources spent on the preventive replacements and

their resulting benefits, that is, reduced failure replacements. The main objective of the cost-based approach to PM planning is to determine the optimum maintenance interval that will balance the system failure repair costs and the PM costs (Jardine, 2005; Lie & Chun 1986; Jayabalan 1992). In some cases, the required replacement policy may be the one that minimizes total downtime per unit time or, equivalently, maximizes availability. Then, the problem is to determine the best times at which replacements should occur to minimize total downtime per unit time. The basic conflicts are that, as the preventive replacement frequency increases, there is an increase in downtime due to these replacements, but a consequence of this is a reduction of downtime due to failure replacements, and the best balance between them should be reached (Jardine 2005; Cassady and Kutanoglu 2003; Ruiz et al. 2007; Pham and Wang 2000).

In the present work, a particular attention to the reliability-based approach has been paid since the reliability is the performance measure that has been taken into account. The model presented in Section 3 is a maintenance optimization model where the objective function is the maximization of the system reliability and the orchestration of the interventions is also taken into account. In literature, few authors focus their attention to the reliability as a performance indicator; they prefer optimizing the maintenance plan with respect to the system availability or to maintenance costs. In general, the reliability is only taken into account as a constraint of the optimization model.

Next to the decision regarding when is more convenient (under the cost point of view or under the reliability point of view) to perform a PM, if the concept of imperfect maintenance is introduced in the optimization model, the additional decision regarding what type of PM to perform has to be taken (Lie and Chun 1986; Jayabalan 1992).
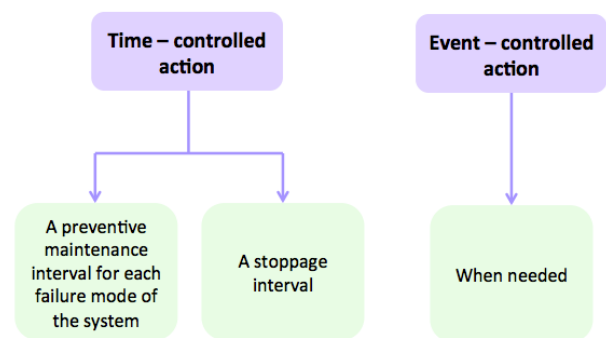

Figure 1: different types of maintenance actions

Maintenance interventions can be performed when needed (event-controlled actions) or at regular intervals (time-controlled action) (Lie and Chun 1986; Kong et al. 2003). In particular, in the latter case, two sub-cases can be adopted. For each failure mode i of the system, the preventive maintenance interval T_{pi} that allows the fulfilment of an objective function can be found (maximization of reliability, minimization of maintenance costs, etc.) or a stoppage interval T_p can be found and, whenever a system stop occurs, the decision about on which failure mode to act is taken. Performing more than one intervention when there is a system stoppage can lead to cost

savings. This possibility is known as "grouping" of preventive maintenance. The joint replacement problem is extensively addressed in literature, but no paper links this problem to a strong analysis of the reliability of the system (Anon 1997; Nicolai 2006).

The proper balance between planned and unplanned maintenance should be reached in order to exploit the available interventions in the best possible way. Planned maintenance percentage (PMP) is one of the most widely used measures of a maintenance department's performance (Momc et al. 2012; Elcheikh et al. 2014). In the presented maintenance optimization model, the optimal balance between the PM and CM policies is found and for each failure mode the optimal percentage of PMs to the total number of interventions is given. This percentage is the one that allows exploiting in the best possible way all the available maintenance interventions for that specific failure mode.

3. THE MAINTENANCE OPTIMIZATION MODEL

The maintenance optimization model that is proposed in the remainder is reliability-centered. Its goal is to plan the preventive maintenance of a generic system subject to n failure modes. The system reliability plot is herein treated as a signal. Thus, a precise and quantitative analysis of it can be made because the mathematical operators of the signal analysis theory can be applied. The system reliability plot is the resulting signal of the combination of the reliability signals of the failure modes of the system. As said, the failure modes are in series-wise configuration: the reliability of the system $R_{sys}(t)$ at a generic time t is given by the product of the reliabilities of the various failure modes at that time instant (Furlanetto and Garetti 2006):

$$R_{sys}(t) = \prod_{i=1}^{n} R_i(t)$$

This system reliability relationship is well known; it is herein applied between reliabilities of the failure modes.

In the paper, the Weibull distribution is used, which is described by means of three parameters: the life parameter α_i, the shape factor β_i and the location parameter γ_i.

In the model both the average system reliability R_{avg} and the minimum system reliability R_{min} are taken into account. This is an innovative aspect since, generally, in literature the reliability is considered just as a constraint to be respected, i.e. the reliability of the system must be kept above a specified threshold (Das 2007; Doostparast et al. 2014). The two indicators (R_{avg} and R_{min}) are necessary to demonstrate that the orchestration of the maintenance interventions in the planning horizon influences the reliability of the system. An input datum to the model is the threshold value of the minimum system reliability $R_{sys, threshold}$: the system reliability must be always kept above this value.

The system reliability (both average and minimum) can be kept at high level if a lot of maintenance interventions are performed in the planning horizon $T_{horizon}$. On the other hand, performing many interventions leads to high maintenance costs. Since the maintenance costs must be kept at reasonable values, it is assumed that an input datum to the model is the

maximum number of interventions $N_{max, i}$ on the failure mode i that can be done in the planning horizon.

The maximum number of interventions $N_{max, i}$ on the failure mode i and the threshold value of the minimum system reliability $R_{sys threshold}$ are related to the length of the planning horizon $T_{horizon}$. In fact, if too little money is spent in maintenance during a time window equal to the planning horizon, the $N_{max, i}$ (with $i=1:n$) assumes low values and the system reliability can achieve local values that are lower than the threshold. This is a typical situation in which, without starting any optimization, the initial data do not allow a feasible solution. In this case, the initial data must be changed; the first possibility is adding more interventions (higher $N_{max,i}$) but, as a consequence, more money in the maintenance activities should be invested; the second possibility is lower the threshold value $R_{sys threshold}$ but this is not always possible due to safety reasons.

The proposed maintenance optimization model can be used to understand the attainable system performance (in terms of reliability) with specified input values of $N_{max, i}$, $T_{horizon}$ and $R_{sys threshold}$.

The main output of the model is the maintenance plan, which contains the indication about *when* to perform a PM and on *which* failure mode. So, depending on the method that is used, the indication of the optimal stoppage interval T_p or of the optimal preventive maintenance intervals T_{pi} ($i=1:n$) is the output. The criterion used to select the best stoppage interval or the best preventive maintenance interval is the maximization of the average system reliability.

The model, as said previously, deals with preventive maintenance but random failures cannot be eliminated and so both the preventive and corrective policies are taken into account. It is assumed that the effect of a PM on the failure mode i is the restoration to one of the reliability curve $R_i(t)$ of that failure mode. So the preventive maintenance is perfect and it restores the equipment, for the specific failure mode, to an *as-good-as-new* condition. On the contrary, the corrective maintenance (CM) leaves the equipment in an *as-bad-as-old* condition. Indeed, a CM on a failure mode FM_i does not influence the reliability curve $R_i(t)$.

A precious information is the subdivision of the maintenance workload between the preventive and the corrective policies for every failure mode, i.e. the indication about how many of the total interventions $N_{max, i}$ must be dedicated to the PM policy ($N_{i,prev}$) and how many to the CM one ($N_{i,corr}$). An output of the model is the optimal percentage $\%_{i, optimal}$ for every failure mode that discriminates between CM and PM policy.

Due to the fact that only the preventive interventions cause an increase of the reliability (it is one of the hypotheses of the proposed approach), the optimization assigns to the CM policy as few maintenance interventions as possible because as many as possible interventions should be assigned to the PM policy, reaching, in this way, higher system reliability. It is not possible to assign all the available interventions to the PM policy (even if this solution would lead to the maximum reliability) because the system is always subject to random failures.

Without the maintenance plan (and so without the indication of the preventive maintenance interval T_{pi} or of the stoppage interval T_p), it is not known how many of the total

interventions must be dedicated to the PM policy and how many to the CM one. The reason is that the frequency of the maintenance interventions influences the number of CM interventions to be performed in the planning horizon. In fact, the number of failures (and so of CMs) of a failure mode i is a function of the preventive maintenance interval T_{pi}: if very frequent PMs are performed, the number of CMs that are expected in the time horizon is small; vice versa, if little attention is paid on the preventive maintenance policy, the expected number of failures increases. So it is evident that the chosen maintenance plan influences the balance between the two maintenance policies.

An input datum to the model is a first attempt subdivision of the maintenance workload between PM and CM for each failure mode: $\%_i$ for i=1:n.

So the goal of the proposed model to plan the preventive maintenance is twofold. The maintenance plan in output maximizes the average system reliability and exploits in the best possible way all the available maintenance interventions, properly splitting them between the two maintenance policies. The objective function of the model is the maximization of the average system reliability and this can be achieved by means of three actions:

- According to the method used, finding the optimal stoppage interval T_p or the optimal preventive maintenance intervals T_{pi} (i=1:n);
- Taking into consideration the arrangement of the interventions in the planning horizon;
- Assigning as many as possible interventions to the PM policy.

Two optimizations are done in the proposed model, one is named *external* and one *internal*. The *internal* optimization, given certain input data and constraints, tries to maximize the reliability of the system by means of finding the optimal stoppage interval T_p or the optimal preventive maintenance intervals T_{pi} (i=1:n), depending on the method used. The result of the internal optimization is an optimal maintenance plan, where the word *optimal* refers to the fact that it is the plan that guarantees the maximum system reliability with that given input data. Nevertheless, the plan is a possible optimal maintenance plan, where the word *possible* refers to the fact that it is not said that it guarantees the optimal balance between the two maintenance policies. This is granted by the *external* optimization. It has to enable the verification that the proposed maintenance plan splits properly the workload between PM and CM policies, i.e. that the proposed maintenance plan assigns as many as possible interventions to the PM policy.

The input and output data and hypothesis of the maintenance optimization model are the following:

Input data
- The Weibull parameters of the failure modes.
- The maximum number of interventions $N_{max,\ i}$ for each failure mode i, either preventive and corrective one.
- The threshold value of the minimum system reliability $R_{sys,\ threshold}$. The system reliability must be always kept above this value.
- The length of the planning horizon $T_{horizon}$.

- The initial subdivision of the maintenance workload between preventive and corrective policies for each failure mode: $\%_i$ for i=1:n (where $\%_i$ is the total number of interventions that can be performed on the failure mode i destined to the PM policy).

Output data:
- The optimal maintenance plan: *when* to perform a PM and on *which* failure mode. Depending on the method that is used, the indication of the optimal stoppage interval T_p or of the optimal preventive maintenance intervals T_{pi} (i=1:n) has to be reported.
- For each failure mode, the optimal percentage $\%_{i,optimal}$ that discriminates between PM and CM policies.
- For each failure mode, the total number of preventive and corrective interventions that must be performed in the planning horizon ($N_{i,\ prev}$ and $N_{i,\ corr}$).
- The calculation of the average system reliability R_{avg} and the minimum system reliability R_{min}.
- The number of non-exploited interventions on each failure mode (this value can also be zero) $N_{i,\ residual}$ (w.r.t. the $N_{max,\ i}$). This happens when, for example, with the optimal T_{pi} for the FM_i not all the available interventions are exploited while using a lower PM interval would lead to an unfeasible solution (not enough interventions at disposal).

Hypotheses:
- The product of the reliabilities of the various failure modes gives the reliability of the system (series-wise configuration).
- The effect of a PM on the failure mode i is the restoration to one of the reliability curve $R_i(t)$ of that failure mode. So the preventive maintenance is perfect and it restores the failure mode to an *as-good-as-new* condition.
- The corrective maintenance leaves the system in an *as-bad-as-old* condition. A CM on FM_i does not influence the reliability curve $R_i(t)$.

In section 3.1 and 3.2 the external and the internal optimization are discussed deeply.

3.1 External optimization
As previously discussed, the objective function of the model is the maximization of the average system reliability and, in order to fulfil the objective, three actions have to be implemented. The external optimization is devoted to one of these: assigning as many as possible interventions to the PM policy, i.e. providing the best splitting of the maintenance resources between the preventive and the corrective policies.

In this section the internal optimization is considered as a black box: just its output is used without considering the internal computations. The output of the internal optimization is a *possible* maintenance plan, according to the word *possible* definition previously provided.

The iterative process of the external optimization is described in the following (see figure 2).

The maintenance budget tells how many interventions $N_{max,\ i}$ on the failure mode i can be done in the planning horizon. Before having the maintenance plan, it is not known how many

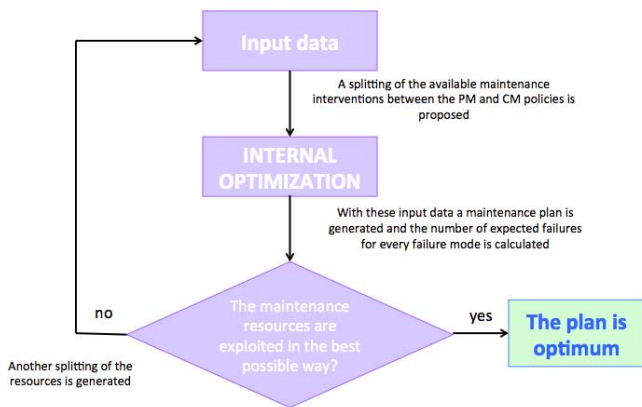of the total interventions must be dedicated to the PM policy and how many to the CM one.

Figure 2: Maintenance optimization model: general schema.

According to a first attempt subdivision ($\%_i$), the maintenance plan (optimum, under the reliability point of view) is generated with the internal optimization and the expected number of failures in the planning horizon is calculated. If the expected number of failures is lower than the CMs at disposal, the situation can be improved. Fewer interventions should be assigned to the corrective maintenance (CM) policy and more to the preventive maintenance (PM) one, aiming in this way at higher system reliability. On the contrary, if the expected number of failures is higher than the corrective maintenance interventions at disposal (according to the given resources), the situation can be improved in the opposite direction: too many maintenance interventions to the PM policy and not enough to the CM one have been assigned. In both cases, a modification of the percentage $\%_i$ that gives the balance between PM and CM policies is needed. But this implies to generate a new maintenance plan, different from the previous one, and so again the expected number of failures has to be calculated and again the comparison with the assigned CM interventions has to be done. The external optimization ends when a situation that can no more be improved is reached. The optimal balance between the two policies for the failure mode i is given by the optimal percentage $\%_{i, optimal}$.

3.2 Internal optimization

The goal of the internal optimization is to find the maintenance plan that allows the system to reach the highest possible average reliability with the specified input data and constraints. So the internal optimization, having the characteristics of the failure modes, the length of the time horizon, the maximum number of preventive interventions, the threshold value of the minimum system reliability, proposes to find the optimal maintenance plan under the reliability point of view.

The internal optimization can be addressed in different ways. In the work, two methods are proposed to generate a maintenance plan in which the reliability of the system is maximized. The *Method 1* has the goal of finding the PM intervals T_{pi} for all the failure modes of the system ($i=1{:}n$) that allows the maximization of the average system reliability. In

the *Method 2*, the goal is to find the optimal stoppage interval T_p and the arrangement of the interventions in the planning horizon that allows the maximum system reliability. So, while in the *Method 1* there is an optimal PM interval for each failure mode of the system, in the *Method 2* the optimum stoppage interval is found (that is the same for all the failure modes) and then the decision about which failure mode must be maintained at every system stoppages has to be taken.

How the arrangement of the maintenance interventions is taken into account in the two methods is now explained. Some solutions (obtained for a particular allocation of the maintenance interventions) can generate a system reliability plot that, at a certain moment, is lower than the threshold value $R_{sys \ threshold}$. The solutions that present this problem are not feasible because they do not respect a constraint and they are discarded.

At the end of the *Method 2*, an average PM interval $T_{pi, \ average}$ for each failure mode i is calculated (Jardine 2005) in order to obtain the expected number of failures for every failure mode.

4. CONCLUSIONS

In the paper a reliability-based maintenance optimization model has been proposed. The objective function according to which the preventive maintenance is planned is the maximization of the system reliability. A first innovative aspect of the model is that the system reliability is treated as a signal and so both the average and minimum system reliability are considered. Thanks to this fact, the arrangement of the maintenance intervention as a factor that influence the reliability can be introduced. A second innovative aspect of the model is the introduction in a reliability optimization model of the concept of balance between preventive and corrective policies.

The model only considers perfect preventive maintenance interventions. The effect of a PM on a failure mode is the restoration to one of its reliability curves (called high-level repair). The method could be improved by means of the introduction of the imperfect maintenance concept. For example, introducing the possibility of restoring the reliability to a value lower than one.

In the proposed maintenance optimization model the CMs does not have any effect on the reliability curve. To improve the model, the possibility that the CM influences the reliability curve can be introduced. Again, the degree of reliability improvement can be complete or partial.

Moreover, in the present work, the failure modes are supposed to be maintainable and independent. Indeed, the optimization model could be improved by means of the modelling of the dependency of the various failure modes or by means of the introduction of non-maintainable failure modes. For example a non-maintainable failure mode could be introduced to model the intrinsic wear of the system as the time passes (Zequeira and Be 2006).

Indeed, the proposed optimization model can also be applied to plan the maintenance of a machine made up of many components in series-wise configuration and described by a Weibull distribution. The model should be modified if other configurations (parallel, stand-by) have to be introduced. Nevertheless, the general schema of the model and its

background are still valid (such as the goal of maximizing the system reliability or the idea of the arrangement of the interventions). It is necessary just to change the formula for the calculation of the system reliability starting from the reliabilities of the components.

An output of the maintenance optimization model is the residual number of interventions $N_{i, \text{ residual}}$. They are non-exploited interventions that are anyway available. A possible future improvement is the possibility of exploiting these residual interventions. If, for example, a failure mode has residual interventions, they could be allocated to another, more critical failure mode to achieve better system performance.

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REFERENCES

Anon, 1997. A Review of Multi-Component Maintenance Models with Economic Dependence. , pp.411–435.

Cassady, C. Richard, and Erhan Kutanoglu. "Minimizing job tardiness using integrated preventive maintenance planning and production scheduling." IIE transactions 35.6 (2003): 503-513.

Castro, I.T., 2009. A model of imperfect preventive maintenance with dependent failure modes. *European Journal of Operational Research*, 196(1), pp.217–224. Available at: http://dx.doi.org/10.1016/j.ejor.2008.02.042.

Das, K., 2007. Machine reliability and preventive maintenance planning for cellular manufacturing systems. , 183, pp.162–180.

Dekker, R., 1996. Applications of maintenance optimization models : a review and analysis. , 51, pp.229–240.

Doostparast, M., Kolahan, F. & Doostparast, M., 2014. A reliability-based approach to optimize preventive maintenance scheduling for coherent systems. *Reliability Engineering and System Safety*, 126, pp.98–106. Available at: http://dx.doi.org/10.1016/j.ress.2014.01.010.

Elcheikh, M. et al., 2014. Uncertainties in Forecasting Maintenance Costs for Asset Management : Application to an Aging Canal System. , (Coleman), pp.1–12.

Fedele Fedele, Furlanetto Luciano, Saccardi Daniele, 2004. Progettare e gestire la manutenzione, Mondadori.

Furlanetto Luciano, Garetti Marco, Macchi Marco, 2006. Principi generali di gestione della manutenzione, FrancoAngeli.

Holgado, Maria; Macchi, Marco; Fumagalli, Luca (2015). Maintenance Business Model: a concept for driving performance improvement. pp.159-176. In International Journal of Strategic Engineering Asset Management - ISSN:1759-9733 vol. 2 (2).

Jardine Andrew K.S., A.H.C.T., 2005. *Maintenance, Replacement, and Reliability: Theory and Applications*, CRC Press, Taylor and Francis.

Jayabalan, V., 1992. Cost Optimization of Maintenance Scheduling for a System with Assured Reliability. , 41(1), pp.21–25.

Kong, J.S. et al., 2003. Life-Cycle Reliability-Based Maintenance Cost Optimization of Deteriorating Structures with Emphasis on Bridges. , 129(6), pp.818–828.

Lie, C.H. & Chun, Y.H., 1986. An Algorithm for Preventive Maintenance Policy. , (1), pp.71–75.

Lin, D., Zuo, M.J. & Yam, R.C.M., 2000. Sequential Imperfect Preventive Maintenance Models with Two Categories of Failure Modes.

Lopez Campos, M.A., Fumagalli, L., Gomez Fernandez J.F., Crespo Marquez A., Macchi M. (2010). UML model for integration between RCM and CBM in an e-Maintenance architecture. (pp. 133- 138). In: 1st IFAC Workshop, A-MEST'10, Advanced Maintenance Engineering, Services and Technology. Lisboa, Portugal.

Macchi M., Garetti M., Centrone D., Fumagalli L., Pavirani G.P., 2012a. Maintenance management of railway infrastructures based on reliability analysis. RELIABILITY ENGINEERING & SYSTEM SAFETY, 104, pp. 71- 83.

Macchi M., Kristjanpoller F., Garetti M., Arata A., Fumagalli L., 2012b. Introducing buffer inventories in the RBD analysis of process production systems. RELIABILITY ENGINEERING & SYSTEM SAFETY, 104, pp. 84-95.

Momc, V., Papic, V. & Vujanovic, D., 2012. Expert Systems with Applications Evaluation of vehicle fleet maintenance management indicators by application of DEMATEL and ANP ˇ ilovic. , 39, pp.10552–10563.

Nakagawa, T., 2005. Maintenance Theory of Reliability, Spinger.

Nicolai, R.P., 2006. Optimal Maintenance of Multi-Component Systems : a Review.

Pham, H. & Wang, H., 2000. Optimal (τ , T) Opportunistic Maintenance of a k -out-of- n : G System with Imperfect PM and Partial Failure.

Ruiz, R., García-díaz, J.C. & Maroto, C., 2007. Considering scheduling and preventive maintenance in the flowshop sequencing problem. , 34, pp.3314–3330.

Tsai, Y., Wang, K. & Teng, H., 2001. Optimizing preventive maintenance for mechanical components using genetic algorithms. , 74.

Vasili, M., Hong, T.S. & Ismail, N., 2011. Maintenance optimization models : a review and analysis. , pp.1131–1138.

Vatn, J., Hokstad, P. & Bodsberg, L., 1996. An overall model for maintenance optimization. , 8320(95), pp.241–257.

Zequeira, R.I. & Be, C., 2006. Periodic imperfect preventive maintenance with two categories of competing failure modes. , 91, pp.460–468.

Zio Enrico. Reliability engineering: Old problems and new challenges. Reliability Engineering and System Safety, Elsevier, 2009, 94, pp.125-141.