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Abstract: More and more equipment manufacturers are contracting with customers for maintenance planning (MP) of their equipment; this maintenance being either corrective, preventive or predictive. Due to the costs involved, customers are increasingly asking for a business case justifying the maintenance plan. This paper describes a study conducted with the MATISA Company, a track construction and renewal train manufacturer, and the business case for the equipment MP put forward to a customer. The concept developed consists of a method enabling the Company to provide a systematic explanation of the adopted maintenance strategy based on a joint cost-availability analysis regarding the 'critical' components. We begin by presenting MATISA practice, followed by a brief review of equipment maintenance principles. We then present the MATISA business case, and conclude with some remarks about the prospects for the method adopted and its generalizability from this experimental study.

Keywords: maintenance, efficient maintenance planning, cost, availability.

1 Context introduction

Founded in 1945, the MATISA Company supplies specialised trains and machines to build, renew, maintain and measure railway tracks. Over time and given the tonnage involved, tracks are subject to deformation due to slipping, infiltration or transformation of the ballast. When the deformation becomes excessive, it is necessary to reduce or even stop rail traffic. Railway companies thus have to regularly maintain their tracks using a ballast tamping machine (BTM).

The process comprises levelling and lining the track (detail A in Fig. 1), adding and compacting some new ballast to reposition the track correctly. The compacting operation entails transmitting vibrations to the ballast by means of several pickaxes dipping into the ballast (detail B in Fig.1). This tamping, depending on the parameters defined, (number of insertions, tightening time depth) enables the track geometry to be processed at a speed of up to 1200m / h.

After the operation, the ballast is compacted enough (detail C in Fig. 1), to allow trains to travel over it without deformation of the track. This equipment is subjected to strong mechanical constraints sometimes due to heterogeneity of the ballast, so they need frequent maintenance.

Fig. 1: Ballast tamping machine in operation

Four years ago, one of MATISA's customers signed a supply contract for 14 BTMs including MP in a context of high equipment availability and high costs. For the first time a review clause was added regarding the MP cost. MATISA was thus faced with a new problem: "how do we justify our MP proposal?" In this instance a project called Efficient Maintenance Planning (EMP), was launched connecting two laboratories of the University of Savoie Mont-Blanc. The idea was to use data from actual use of the BTM, and process it to produce a reliability model for the computation of maintenance costs.

The aim of the study is the development of a method enabling the MATISA company to construct a MP business case according to cost and availability objectives. This method systematically computes costs and availability for each possible maintenance type to choose the most appropriate one. This paper summarises the method and is organised as follows. In Section 2 we briefly review the three types of maintenance principles, as well as essential computation approaches. Section 3 covers the MATISA case study. The method developed is presented, including three steps: critical component identification, processing of reliability data and maintenance costs, and availability computation. We conclude with some remarks about the method adopted.

2 Maintenance basics

In the Reliability-Availability-Maintainability-Safety (RAMS) approach, the purpose of maintenance is to ensure equipment reliability, availability and safety to produce profitable products or services [1]. In this sense, the European Norm characterises maintenance as: "*Together with all technical, administrative and management staff, during the lifecycle of a property, to maintain or reinstate a given condition so it performs its required function*" [2]. Ensuring a good level of maintenance involves both the designer and user of the equipment: the designer must build reliable and maintainable equipment, and the user must use and maintain it correctly. These two aspects are connected in the maintenance plan which must be prepared before using the equipment [3]. This maintenance plan is applied and thus adapted by the user [4]. On the one hand, it enables the maintenance service to be defined, the type of maintenance to be carried out and the associated schedule, and on the other hand, the operational aspects of the maintenance activity. Operational aspects are usually carried out well by companies due to their knowledge of supplier equipment and skilled maintenance teams [5]. Maintenance choice is not so clear because it depends on equipment technology, the user's company objectives, the economic context and equipment behaviour, according to the RAMS approach [6].

Traditionally, companies choose the type of maintenance based on RAMS objectives. They must make trade-offs between several types of maintenance defined as: improvement, preventive, predictive and corrective [7]. In the maintenance planning definition only the last three types are considered.

- Preventive maintenance consists of avoiding operational failure by return to a state of functioning 'as good as new', thus increasing production capacity and reducing the probability of failure rendering it unable to produce [8].
- Predictive maintenance occurs when maintenance operations are launched according to the actual condition of the equipment, most often provided by sensors and analysis techniques based on artificial intelligence [9].
- Corrective maintenance consists of addressing equipment failure to return it to the 'as good as new' state of functioning [10].

When equipment is complex, involving hundreds of components based on different technologies with multiple interrelationships, several types of maintenance are often used for the different parts of the equipment. The correct choice of maintenance ensures equipment safety thanks to standards or dedicated tools such as failure trees, criticality analysis [11] or specific instructions such as those provided by standards [12]. When the choice remains over, objectives of reliability and availability can be considered through compromise [13] [14]. The literature review shows that a key purpose of maintenance planning involves reliability optimization [15]. However, availability, which combines reliability, maintainability and logistics is also very important. Moreover, availability-based maintenance introduces the aspect of cost in maintenance choice [16] and more precisely the direct maintenance costs and the indirect costs generated by equipment failure [17]. We have adopted this approach, which relies on a cost computation model linking reliability behaviour and economic data [18], in our study.

3 Proposed computation method

The proposed model is described based on the EMP study. In a first step the BTM components are ranked according to the cost of replacement parts. Then the failure of the costliest components replaced is processed to identify their reliability behaviour. The possible maintenance types are explored with the BTM designer, and the associated costs are computed from an estimate of the economic data. Finally, the different maintenance types are compared and recommendations are given. Provision of recommendations to the user is not considered in this study.

3.1 Choice of the critical components

Data can be collected from the information systems (IS) of the different stakeholders such as the customer, the MATISA After Sales subsidiary and MATISA headquarters. Knowing that the IS were not interoperable, human processing must also be done. The first file extracted from the Enterprise Resources Planning (ERP) database presents the date, reference number, equipment concerned, quantity, and cost of the consumed part for each component. Some information was missing such as the type of maintenance trigger, component consumption type (preventive vs corrective) and location of the component on the equipment (the same component may be present in different parts of the equipment) and the operating duration of the replaced component (or for components involved in movement of the equipment, the distance travelled).

We selected the first equipment delivered to the customer as having the longest lifetime. To reduce manual recovery of information, we carried out a cost Pareto analysis of the replaced parts where 11% of the 245 references replaced represent 80% of the costs. Ultimately, the pickaxe was chosen, which represents 8% of the cost with 19 replacements.

3.2 Cost model

A maintenance policy is established to manage each component using common procedures such as the preventive maintenance interval or predictive maintenance. Therefore, the exact definition of the maintenance type should follow a predefined framework. Knowing that for pickaxes, the possible maintenance types are corrective, preventive and predictive (based on human inspection which has so far appeared to be easier and more efficient than an instrumentation) MATISA has chosen predictive maintenance. For the sake of comparison, the different maintenance types are expressed using the same unit of *euros per hour*.

Corrective maintenance consists of replacing the broken pickaxe(s) with new one(s) as soon as possible, until the equipment is back at the maintenance station. On average the response time before the *Time to Repair* is 4 hrs. Thus, the reduction in speed of the BTM due to the reduction in the number of pickaxes involves a production loss of about 20%. So the corrective maintenance cost is the following:

$$C_{Corr.} = C_{Int.} + 0.2PL + DC \qquad (1)$$

where $C_{Int.}$ is the cost of the part and the manpower to replace the part and the administrative procedure, PL is the cost of the total production losses and DC are the damage costs due to the failure. This cost corresponds to a *Mean Time Between Failure (MTBF)* of the equipment, so the cost per hour is the following:

$$C_{Corr./hr} = \frac{C_{Int.} + 0.2 \times PL + DC}{MTBF} \tag{2}$$

Preventive maintenance consists of replacing the pickaxes according to a given interval T for a part corresponding to the reliability function $R(T)$. In fact, it remains a part of corrective maintenance because the failure function $F(T) > 0$. In this case a proportion of $R(T)$ components are replaced in a preventive way, avoiding production losses and damage costs. The T interval must be coherent with the maintenance planning which allows the maintenance team to carry out preventive intervention, daily, weekly, monthly, quarterly and yearly. Note that these interventions can be undertaken during the day knowing the equipment is used only at night between 10 pm to 6 am. So, the preventive maintenance cost is the following:

$$C_{Prev.}(T) = C_{Int.} \times R(T) + C_{Corr.} \times F(T) \tag{3}$$

This cost corresponds to a mean duration computed from the mean used time $m(T) = \int_0^T R(t)\,dt$ for the corrective part given by $F(T)$ and the T interval for the preventive part given by $R(T)$. So, the cost per hour is the following:

$$C_{Prev./hr}(T) = \frac{C_{Int.} \times R(T) + C_{Corr.} \times F(T)}{m(T) \times R(T) + MTBF \times F(T)} \tag{4}$$

Clearly, the preventive cost depends on the T interval and there exists a value T^* which optimizes this cost as shown in Fig. 3.

Predictive maintenance consists of regularly inspecting the pickaxes in the maintenance station before the nightly work of the equipment. Our assumption is that the skill of the maintenance team enables the avoidance of 95% of pickaxe failures, so 5% of corrective maintenance remains. A more refined model could be used if this assumption is not accurate. So, the preventive maintenance cost is the following:

$$C_{Pred.} = \left(C_{Int.} + C_{Insp.}\right) \times 95\% + C_{Corr.} \times 5\% \tag{5}$$

where $C_{Insp.}$ is the mean cost of the inspection of a pickaxe. This cost corresponds to a mean duration of the $MTBF - d$ where d is the wasted time between the preventive intervention and the avoided failure.

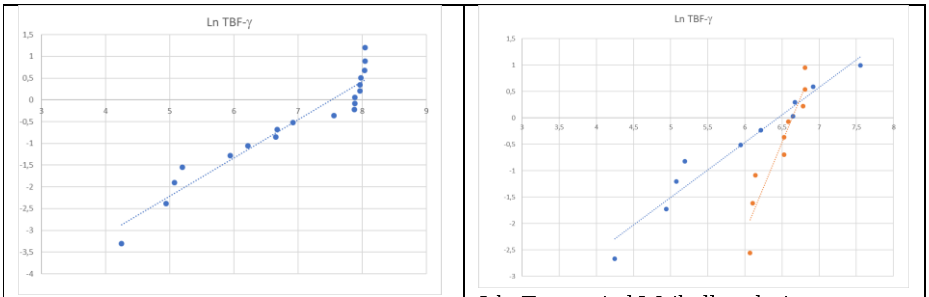
$$C_{Pred./hr} = \frac{\left(C_{Int.} + C_{Insp.}\right) \times 95\% + C_{Corr.} \times 5\%}{\left(MTBF - d\right) \times 95\% + MTBF \times 5\%} \tag{6}$$

3.3 Cost-availability analysis

Let us now consider the reliability data for the computation of $F(T),\ R(T),\ MTBF,\ m(T)$; the economic data $C_{Int.},\ PL,\ DC,\ C_{Insp.}$ and d are given by the user. Faced with this unusual demand for the equipment history, the user agrees to only supply the date of the pickaxe change, so 19 corresponding TBF are deduced, supposing that all of the replacements correspond to failures. The reliability data are then considered to be complete. If user data were more precise, some preventive intervention could be identified. In this case the data processing should be adapted to take into account censored data.

Using only one Weibull model, as shown in Fig. 2a, is not satisfactory due to the non-linearity of the data. Therefore, a more complex Weibull model is proposed to distinguish the two clouds of points in Fig. 2b. So, the pickaxe behaviour is modelled by:

- An initial model corresponding to the blue cloud where $\beta = 1.04,\ \eta = 629hrs,\ \gamma = 0hr$. It means that the earliest failures with $\beta = 1.04$ are time independent, so knowing the pickaxe function, they are extrinsic failures due for instance to incorrect use. This point has been confirmed by the MATISA team. For these failures no maintenance is necessary.
- A second model corresponding to the brown points where: $\beta = 4.76,\ \eta = 1019hrs,\ \gamma = 1950hrs$ with. $MTBF = 2906hrs$. It means that the failure rate is rapidly increasing in a phenomenon of accelerated wear $\beta = 4.76$, after a period without failures $\gamma = 1950hrs$. So, maintenance is required after the 0 failure period.



2.a: One period Weibull analysis

2.b: Two period Weibull analysis

Fig. 2: Weibull regression models for the pickaxe component

Consequently, for the maintenance type recommendation, only the second part of the pickaxe life is considered.

The economic data are known only by the user who does not want to disclose them. However, the MATISA expert has a high degree of skill in this area so he provided an estimate of this data with $C_{Int.} = 3490€,\ PL = 240000€,\ DC = 3000€,\ C_{Insp.} = 1000€$ and $d = 80hrs$. By applying (2), (4) and (6) the maintenance costs are:

$$C_{Corr./hr} = \frac{3490 + 0.2 \times 240000 + 3000}{2906} = 6.36€ / hr$$

$$C_{Prev./hr}\left(T^* = 2200\right) = \frac{3490 \times 99.88\% + 54490 \times 0.12\%}{2200 \times 99.88\% + 2177 \times 0.12\%} = 1.59€ / hr$$

$$C_{Pred./hr} = \frac{\left(3490 + 1000\right) \times 95\% + 6.36 \times 5\%}{\left(2906 - 80\right) \times 95\% + 2906 \times 5\%} = 1.42€ / hr$$

We note that theoretical optimal T interval is $T^* = 2320$. Given the organisational constraints, preventive maintenance will occur every nine months corresponding to about $T^* = 2200$ as shown in Fig. 3.

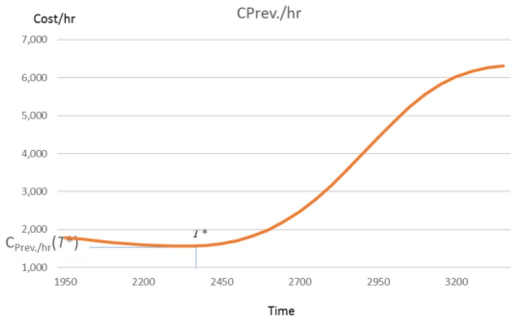


Fig. 3: Preventive maintenance cost evolution according to T

From this cost computation it appears that predictive maintenance is better, with a cost advantage of about 14% compared to preventive maintenance. Corrective maintenance is much more expensive and must be avoided. Before making this choice the user has to check whether the unavailability of the machine is not too high. Table 1 below gives the corresponding unavailability of the machine due to pickaxes according to the type of maintenance. We underscore that corrective maintenance gives the worst result with a high level of unavailability. Preventive maintenance is much better than predictive, but both ensure a low level of unavailability which is consistent with the user requirement.

Table 1: Unavailability associated with each type of maintenance.

Type of maintenance	Unavailability (Unav.) $Unav.$
Corrective	$Unav. = \frac{0,2 \times 4 \times 16}{2906} = 0,440\%$
Preventive	$Unav. = \frac{0,2 \times 4 \times 16 \times 0,12\%}{2200 \times 99,88\% + 2906 \times 0,12\%} = 0,001\%$
Predictive	$Unav. = \frac{0,2 \times 4 \times 16}{2813} \times 5\% = 0,022\%$

Therefore, at the conclusion of this analysis, the recommendation remains the same as initially, i.e., undertaking predictive maintenance prior to nightly equipment use. However, if the availability criterion becomes very important for the user, preventive maintenance could be a better alternative. The difference this time, is that the MATISA company can explain the choice to its customer. Certainly, a robustness analysis should complete this study, namely by investigating the production loss value or the reliability model which have substantial effects on the cost computation.

We note that the question of the interoperability of the IS will be a key factor in generalising this analysis to the entire set of critical components. Thus, a Product Breakdown Structure (PBS) code to define the location of each component on the equipment is required for correct information processing.

4 Conclusion

This article presents a real maintenance case study in a context where users ask suppliers for justification of proposed maintenance planning. A method including critical component selection, potential types of maintenance identification, reliability behaviour modelling and maintenance cost computing is proposed. It allows the partners to share knowledge about equipment, be confident, justify and possibly adjust and improve the current maintenance regime. Two conclusions can be considered. The first concerns the MATISA company which can generalize the method to the entire set of critical components and integrate the processing of data in its future interoperable maintenance information system, after opting to manage the PBS code in the equipment's master data. Beyond the MATISA context, such a method could be applied to any complex equipment if both technical and economic data are available. The second one is more relevant in the academic context. It concerns the updating of reliability data (with increasing use of the equipment, the number of failures will increase and the reliability model may change, affecting the maintenance recommendation). Introducing real-time reliability and cost analysis could be of interest to both the equipment manufacturer and the user.

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