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Data Mining to Reduce Unscheduled and the Total Number of Maintenance Visits

***Abstract* – We present an approach to reduce the number of maintenance visits for medical equipment using predictive maintenance. We consider, that repair recommendations for an ensemble of equipments close to each other can be combined to one maintenance visit. For that purpose two recommenders that are trained with different false positive rate limits are used. The more sensitive recommender, e.g. the one with a higher false positive rate, is used to create repair recommendations that are only considered positive if a maintenance worker is already on-site or nearby. In case the travel costs are more expensive than the technical component to be replaced in the medical equipment itself, it is shown that a greedy recommender, that will recommend a replacement very early and possibly waste more lifetime of that component, is helpful. The benchmark results show clearly that this approach can actually reduce the total number of visits for the cost of more components being replaced.**

***Keywords* – data mining; predictive maintenance; maintenance strategy; maintenance grouping**

I. Introduction

The importance of proactive maintenance can nowadays be motivated by countless examples [1]–[9]. A sudden incidence can cause many lost working hours in a productive environment, which can be extremely expensive. Proactive maintenance is used to reduce the high cost of the unscheduled downtime, e.g. in nuclear power plants [2], for airplane engines [9] and medical equipment [4], [7], to only mention a few applications. In many cases, there is no local maintenance worker available to replace the affected component. Thus, the downtime after a sudden failure increases even more, because of the additional travelling time, what should be prevented. Proactive maintenance in principle aims to avoid this situation and is preferred over any reactive strategy if it can be implemented in a cost-efficient way.

Proactive maintenance can be divided in time- or usage-based preventive maintenance and reliability-centered or predictive maintenance. Several studies show that for most parts predictive maintenance performs better and is more beneficial than preventive maintenance [1], [8], [10]. However, the problem with predictive maintenance is the amount of false predictions, i.e. the replacement of mostly faultless components. Another problem are the setup costs, especially the travel cost, which are more expensive than the maintenance action itself in many cases. The financial loss is particularly high if the same location or locations close to each other have to be visited several times in a short time span due to several repair recommendations. The grouping of maintenance actions should be preferred in such a case to reduce the number of maintenance visits in total. In case of comparatively high travel costs it is preferable to reduce the number of visits in total.

This paper presents an approach to reduce the total number of maintenance visits by combining replacements of components from the same or any nearby equipment.

The remainder of this paper is organized as follows. Section II describes the importance of reducing maintenance visits in total. Similar approaches are described in Section III. Section IV describes the methods used for finding the best maintenance strategy to reduce the number of visits. Results on real observations of medical equipment are shown in Section V. Section VI concludes this paper and gives an outlook to future work on the topic.

II. Problem Formulation

This work describes a method for reducing the total number of maintenance visits for multiple machines in different locations. If the number of maintenance visits is raising drastically, the approach to reduce unscheduled downtime is not sufficient anymore. To reduce the number of visits, multiple maintenance actions should be grouped together – to one visit.

In our predictive maintenance approach two repair recommenders are used in combination. First, the initial repair recommender (IRR), takes observed measured values as input and outputs repair recommendations that require a maintenance visit for the replacement of a component. The second recommender is called 'Already There Repair Recommender (ATRR)' which is more sensitive and thus publishes repair recommendations more frequently than the IRR. However, those recommendations are only considered if there is a maintenance visit nearby. In this case it is possible to combine the repair recommendation from the IRR with the already there repair recommendation from the ATRR. That means two or more repairs are carried out in one visit. Both recommenders are based on naive bayes classifiers. The threshold to separate unfaulty and possibly faulty components is learned with history data about observed measured values, repair incidences and incidence dates, where a failed component had to be replaced. The approach is based on an optimization model that defines the values to be optimized and the criteria for the optimization. Those usually involve the number of true positives (TP), i.e. repair recommendations for a faulty component, and false positives (FP). An FP indicates an unnecessary repair due to a repair recommendation. The test data used to validate the recommender contains actual incidence dates. To decide whether a repair recommendation is a TP or FP an incidence window is used, as shown in Fig. 1. If there is an incidence in this particular timespan after the recommendation it is considered as a TP otherwise as an FP. The incidence window depends on the average lifetime of the analyzed component.

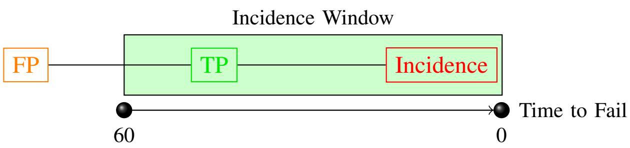

Figure 1. Determining TP's and FP's with the incidence window

Because the number of TP's and FP's is known, both recommender can use an optimization model with a certain false prediction rate (FPR) limit. The FPR is calculated with $FPR = \frac{\#FP}{\#TP+\#FP}$. The optimal decision rule is the one that stays within this limit and yields the highest true positive rate (TPR), which is calculated with $TPR = \frac{\#TP}{\#Incidences}$, as well. Using an FPR limit is a very good optimization strategy for the ATRR since it allows to set the sensitivity of the recommender much more precise. The FPR limit for the ATRR is set higher than for the IRR. Accordingly, the ATRR will make more false predictions but can also detect an incidence much earlier.

III. Related Work

Several approaches about using proactive maintenance to improve maintenance have been published already [1]–[9]. The idea to group maintenance visits is discussed frequently as well. In [13] Bouvard et al. presented a method to optimize the maintenance planning for a commercial heavy vehicle and analyzed static and dynamic methods for grouping maintenance actions. They concluded that dynamic methods can improve the maintenance planning due to the additional information on degradation features. However, they only concentrate on one vehicle instead of multiple vehicles at a time. Van et al. presented in [11] a dynamic grouping maintenance strategy for multi-component systems. In [12] they extended their strategy by integrating optimization algorithms to help constructing an optimal maintenance planning with a given availability constraint under limited repairmen. However, their approach does not yet support condition-based maintenance.

Our novel approach extends a condition-based maintenance approach by using two instead of one repair recommender to allow the grouping of maintenance actions. Furthermore, we consider grouping maintenance activities for multiple machines close to each other instead of focusing on one machine. This way we can concentrate on the most critical components for each machine separately.

IV. Simulating Maintenance Strategies for an Ensemble of Machines

To measure the effectiveness of our approach we simulated the usage of three different maintenance strategies for the same ensemble of machines each and compare the number of unscheduled maintenance visits (V_u), the number of scheduled maintenance visits (V_s) and the total number of replaced components (R). Therefore, the number of original replacements (R^*) and their execution dates have to be known.

The first simulated strategy is a reactive maintenance approach, the "Reactive Strategy". Therefore, the number of replacements is the same as originally, $R^r = R^*$, and the number of unscheduled visits equals the number of replacements since components are only replaced if they have failed already. However, if multiple components are analyzed, the replacements of different components for one or multiple machines close to each other at the same time can be combined to one maintenance visit, so $V_u^r \leq R$. Since it is in the general case difficult to measure for which replacements it may be possible to combine them, we assume here the worst case. That is no visits are combined and only one component is replaced at each visit, so $V_u^r = R$. No scheduled visits exist with this strategy - $V_s^r = 0$. An example with three incidences (Inc) for three different machines (M1-3) is given in Fig. 2.

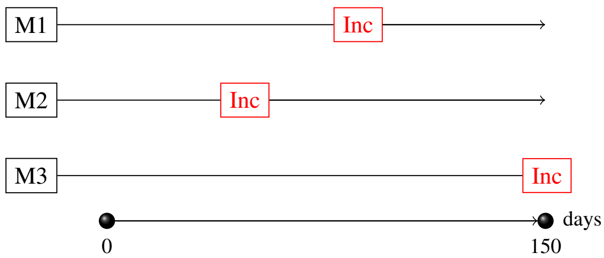

Figure 2. Reactive maintenance with three different machines: all three maintenance visits are unscheduled. Three replacements are executed and no scheduled visits exist. $V_u = 3, V_s = 0, R = 3$

The second simulated strategy, the "RR Strategy", uses a simple predictive maintenance approach with one repair recommender. For this strategy, the maximum number of scheduled maintenance visits can be calculated with $V_s^{rr} = \#TP + \#FP$. If multiple components are considered, the rule for combining maintenance visits regarding multiple components of one machine, as with the reactive strategy, can be applied as well. So the actual number may be even smaller. That is simple if two or more scheduled visits can be combined. However, it is difficult to determine if a scheduled visit can be combined with one or more unscheduled visits. This would always result in one scheduled visit if another component of the same machine or a machine nearby fails when a maintenance worker is on-site. For this work we assume pessimistically that no unscheduled visits can be combined with a scheduled visit, so the number of unscheduled visits can be calculated with $V_u^{rr} = V_u^r - \#TP$. The total number of replacements can be calculated using $R^{rr} = V_s^{rr} + V_u^{rr}$. Fig. 3 shows the example from Fig. 2 with repair recommendations instead.

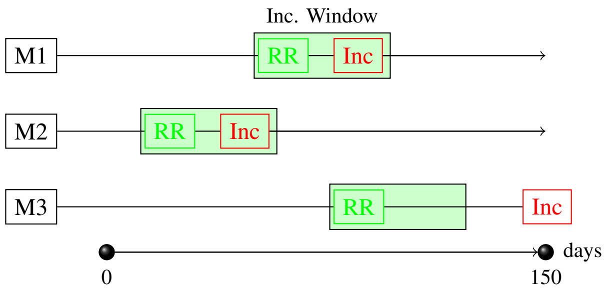

Figure 3. With repair recommendations: two of three visits are scheduled now. One unscheduled visit remains and one unnecessary replacement is executed as well as another scheduled visit which results in three scheduled visits and four replacements in total. $V_u = 1, V_s = 3, R = 4$

The third and last simulated strategy, the "ATRR Strategy", uses, in addition to the previous strategy, already there repair recommendations to combine maintenance visits for one or multiple equipments nearby. For the simulation, the incidence window for the ATRR is extended to the average lifetime of the component, but not larger than three times the incidence window for the IRR. That is done, because due to the aggressivity of the ATRR, most of the replacements would be considered as too early with a short incidence window. On the other hand, if the ATRR incidence window is too large, every replacement would be considered beneficial, so using the average lifetime of a component is a good compromise.

As mentioned before, already there repair recommendations are only taken into account if a repair recommendation from the first recommender is created at the same time. Accordingly, the number of scheduled visits is always equal or smaller than without the ATRR, $V_s^{atrr} \leq V_s^{rr}$. An already there repair recommendation can prevent a maintenance visit if it is close before a normal repair recommendation. The same applies to unscheduled visits as well, so the number of them is also equal or lower than without the ATRR, $V_u^{atrr} \leq V_u^{rr}$. The benefit of achieving potentially less visits than with the second strategy is payed with more replacements in total. Those will always be at least equal or higher than with one recommender, $R^{atrr} \geq R^{rr}$, since an already there repair recommendation may not prevent another visit, which results in one additional repair. Fig. 4 shows the above example with the third strategy applied.

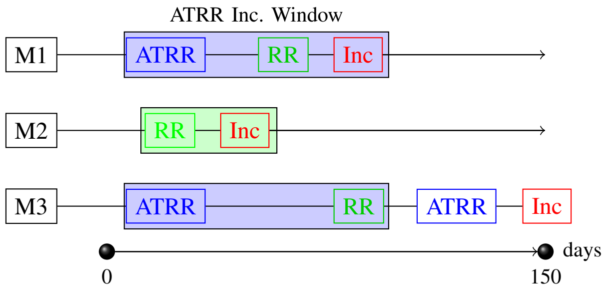

Figure 4. With already their repair recommendations: the scheduled visits can be combined to one visit if the machines are close to each other, although, due to the aggressivity of the ATRR, an unnecessary repair, which does not prevent another unscheduled visit, may be created as well. In this case, the ATRR prevents another unnecessary replacement that would have been executed as well, so nothing changes in comparison to the second strategy for the third equipment. An ATRR without an RR at the same time for an equipment nearby has no effect at all. In total, the results are $V_u = 1, V_s = 1, R = 4$

V. Results for Medical Equipment

The three strategies described above, have been applied to medical equipment of the company Applied Biosystems. More precisely, we use data collected over a timespan of 16 months for 1083 DNA analyzer. For now we concentrate our analysis on one component, the laser only, since, during this time period, it is the only component with a significant number of replacements $R^* = 719$. However, this approach should be more effective using multiple components because that not only allows combining maintenance visits for one machine but for different components as well.

The first recommender was optimized using an FPR limit of 50 percent and an incidence window of 60 days. The FPR limit is very high and thus it should lead to many additional repairs. The ATRR was optimized using an FPR limit of 66 percent. Because the average lifetime of the analyzed component is one year, the incidence window for the ATRR was set to $3 \cdot 60 = 180$ days, which is the maximum length in this case. The results for all three strategies are shown in Table I.

Additionally, the cost for each of the three strategies are displayed. We use a cost model that has been developed in cooperation with Applied Biosystems. In regard to this model the cost for an unscheduled visit (C_u) is USD 4,000. Here we consider the loss due to the unexpected downtime of a machine -the downtime cost (C_d)- with USD 3,500 and the cost for a scheduled visit with USD

500. These USD 500 contain the setup cost (C_s) with USD 450, and the component cost (C_c) with USD 50. In case replacements can be combined to one maintenance visit, the setup cost have to be paid only once for one visit. Accordingly, the total cost for one strategy is calculated with $C_t = V_u \cdot (C_d + C_s) + V_s \cdot C_s + R \cdot C_c$.

Table I. THE RESULTS FOR APPLYING THE THREE DIFFERENT STRATEGIES ON REAL DATA OF MEDICAL EQUIPMENT

	V_u	V_s	R	$C_t(USD)$
Reactive Strategy	719	0	719	2,876,000
RR Strategy	502	434	936	2,225,000 (-651,000)
ATRR Strategy	486	204	955	2,059,250 (-816,750)

The reactive strategy is of course the one with the most unscheduled visits, but it is also the strategy with the least replacements. As expected for the second srategy, the number of scheduled visits is very high due to the high FPR limit. Therefore, only 217 unscheduled visits could be prevented. However, the savings with this strategy are remarkable because it is able to prevent a relatively large amount of unexpected downtime. Since only one component has been analyzed and no replacements could be combined to one visit, the total number of replacements is $R = V_s + V_u = 936$. The ATRR strategy, on the other hand, leads to very good results regarding the number of visits. The number of scheduled visits could be reduced by half because many incidences could be detected much earlier and thus replacements were combined to one maintenance visit. Even some unscheduled visits could be prevented. In some cases the replacements caused by the ATRR could not prevent another visit, so some additional replacements were executed as well. The most important result though, is that the number of total visits could be reduced by 29 compared to the reactive strategy. That led to additional savings over USD 150,000 compared to the RR strategy. This result is important because it shows that with the ATRR strategy a lot more costs can be saved if the setup cost are much higher than the cost for the actual replacement.

VI. CONCLUSION & OUTLOOK

We presented a novel approach for grouping maintenance visits based on predictive maintenance. With a simulation using real observation data from medical equipment we showed that it is possible to reduce the total number of maintenance visits with the proposed method compared to a reactive strategy.

Our next steps include extended benchmarking using different prediction methods and optimization models and adding a penalty function that considers the remaining lifetime of a component in particular instead of using the incidence window for a yes-no decision. Furthermore, we are going to consider multiple components instead of one. We also plan to include the calculation of the optimal route for a maintenance worker for multiple grouped maintenance actions to effectively make use of this strategy.

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