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DESIGNING A DECISION SUPPORT SYSTEM FOR TRUCKS PREDICTIVE MAINTENANCE

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Abstract: the design of a decision support system addressing maintenance management for commercial vehicles is the aim of this work. Seizing the chance offered by an EU-funded project exploring improvements in lifecycle management from smart embedded systems usage, a predictive maintenance algorithm has been designed having the goal to apply predictive maintenance procedures on a real automotive scenario. The described approach represents the backbone of a (still under development) innovative system for the optimisation of maintenance interventions on a fleet of trucks. The new maintenance system is conceptualized in order to collect information and knowledge which can add value to all the stakeholders of the value chain.

Keywords: Decision Support System; Predictive Maintenance; Commercial Vehicles, Scheduling Algorithm

1 INTRODUCTION

Costs related to maintenance interventions are often higher than purchasing prices. This is true in many different branches and, in particular, in the transportation sector (Barnes and Langworthy, 2002).

In various highly technology-based industrial branches, the development of innovative approaches for better managing the maintenance of complex machines have been deeply practised in last years. Passing from approaches meant to optimise the scheduling of maintenance interventions performed on systems breakdown to historical data analysis to better foresee possible future breakdowns. In recent years predictive maintenance methodologies based on real-time monitoring of the actual status of the critical components are growing, especially in the machine tool area (Chu et al., 1998), (Carnero, 2005).

In the automotive sector, the maintenance of vehicle is currently still strongly based on preventive approaches and on system breakdowns. This may consists in an acceptable compromise for private cars and vehicles. Otherwise adopting this approach for commercial vehicles (e.g.: buses, trucks, light commercial vehicles, etc.) is unquestionably wasteful and uneconomical for owners and a more efficient and adequate solution is desirable.

Aiming at this purpose, a Decision Support System (hereinafter: DSS) designed to improve maintenance management on commercial vehicles is presented and described in this paper.

This maintenance management tool is part of a wider project meant to re-define the maintenance procedures to be applied to a fleet of trucks. The truck manufacturer has also in charge the maintenance of the supplied vehicles and as a result of this (still on-going) project, an innovative approach for managing maintenance relying on a predictive-maintenance algorithm is going to be tested.

The main goal of the project is to enhance present maintenance procedures in order to:

- Reduce the number of vehicle stops for maintenance
- Minimise the overall lifecycle costs of the components
- Avoid component breakdowns
- Take into account vehicle availability while planning maintenance interventions
- Take into account maintenance crew availability for performing maintenance

The proposed approach is based on a predictive maintenance algorithm that exploits the advantages resulting from the installation of a set of sensors constantly monitoring the status of a selected bunch of engine components. The entire lifecycle of each component and of the whole vehicle is taken into account since the first stages of the DSS design. Benefits deriving from the implementation and the adoption of this module would influence the different steps of the product lifecycle: according to (Kiritsis, 2003), Beginning of Life activities would be improved thanks to a more complete information concerning past products lifecycles, Middle of Life operations (in this case, especially, maintenance) would be improved exploiting data detected in real-time and, finally, End of Life activities (recycling, retrieval of components) would be improved having a clear picture of the event the product / solution / component has passed through.

2 STATE OF THE ART OF MAINTENANCE

2.1 State of the art in literature

Maintenance policies can be grouped into different bunches (Fedele et al., 2004), (Swanson, 2001), (Bateman, 1995) according to the way the user deals with breakdowns. According to this point of view, three main categories can be used to group maintenance policies: reactive policies, proactive policies, and TPM (Total Productive Maintenance) & RCM (Reliability-Centred Maintenance).

The selected approach belongs to the "proactive maintenance" group and, specifically, to the "predictive maintenance" policies. It was chosen to focus on this kind of approach in order both to make an important step towards the reduction of maintenance costs and to avoid rejections deriving from too-much demanding goals (like TPM and RCM). The proposed approach is innovative especially in comparison to ones usually adopted in the automotive industry.

Proactive maintenance approaches have the goal of avoiding as much as possible system breakdowns. Using historical data, empirical tests and statistical computations, it is possible to put into direct relation the time (working time and/or lifespan) with the probability of system breakdown. What follows is a planning of the maintenance activities that maintains the risk of system breakdown under a pre-defined threshold. In contrast with mere historical data used in preventive approaches, predictive maintenance (also called: condition-based maintenance) is based on data coming from expressly installed sensors, that are devoted to the "measurement" of the actual status of a component, providing a picture of its consumption or wear in order to perform maintenance interventions only when needed (Chan et al., 1997). Using these data it is possible to perform maintenance only when it is actually needed.

Literature on predictive maintenance mainly focuses on machine tools, while rarely vehicles are taken into consideration (Wilson et al., 2003). Moreover, just a few studies (Zhu, 1996) focussed on the development of DSS supporting maintenance on vehicles. According to (Yam et al., 2001) a Decision Support System (DSS) supporting (esp. predictive) maintenance can rely on: knowledge base, analytic hierarchy process, Petri nets, neural networks, fuzzy logic and fuzzy networks, and Bayesian theory. With the design of an Intelligent Predictive Decision Support System (IPDSS) for Condition-Based Maintenance, Yam et al. integrate equipment condition monitoring, intelligent condition-based fault diagnosis and prediction of the trend of equipment deterioration strongly improving the quality of maintenance decisions. Results obtained in the mentioned studies and the lack of knowledge on real benefits connected with applying predictive maintenance on vehicles have prompted us in the here-described work

2.2 Maintenance practices in the case study

Traditional maintenance activities in automotive (Haghani and Shafahi, 2002) can be included in two categories: intervention on system breakdowns and preventive maintenance plans. These two approaches are still largely the most commonly used (Wyrick and Storhau, 2003)

Recent maintenance policies try to avoid component breakdown for two main reasons: on one side the failure of some components (e.g.: brakes) would even jeopardize users' safety. Economical observations are the basis of the second reason. Both private cars' and, especially, buses' and trucks' non-scheduled stops for component replacement would be definitely more costly than planned preventive maintenance interventions.

Also the truck manufacturer of the here-described case acts in this way: it provides the user with a garage for assistance and component replacement on breakdown but, above all, defining preventive maintenance plans it aims at avoiding non-scheduled vehicle stops.

As already described, present maintenance procedures performed by the truck manufacturer are mainly based on preventive maintenance and, fewer, on substitution of components on breakdown. Preventive maintenance activities are grouped into three kinds of services: Standard Service, Extra-Plan Operations and Temporal Operations.

Standard Services are performed according to a pre-defined schedule: after a given mileage the truck has to change engine oil and air filter and, moreover, some inspections on engine, brakes, steering wheel,etc. are performed

Extra-Plan operations are complementary to Standard Service activities and they are performed on specific components (not actually maintained within the Standard Service plan). After a given mileage, automatic gear oil has to be changed and the automatic gear cleaned up, and so on. Such activities are usually planned consistently with the Standard Service plan, in order to reduce the number of stops of the truck.

Temporal operations are mainly related to climatic and seasonal aspects and not to mileage. The radiator has to be cleaned up, pollen filters have to be controlled and, in case, replaced, engine cooling liquid has to be replaced, etc. These activities related to the seasons and to the environmental conditions (temperature, dampness, etc.) are also usually planned taking into consideration the Standard Service plan, in order to minimize stops for maintenance.

3 THE PROPOSED APPROACH

Many studies (Barnes and Langworthy, 2003), (Purdy and Wiegmann, 1987) highlighted the magnitude of maintenance costs on the overall costs for the truck (or generic automotive) life cycle. The described system addresses the reduction of this kind of costs through the development of a pilot approach meant to improve maintenance procedures on three critical components (air filter, brakes and engine oil) for a fleet of trucks. Predictive maintenance tools are the basis of the proposed work. Having a real-time monitoring of the actual status of components of the truck allows the fleet administrator to effectively and efficiently manage the maintenance activities on each truck. Data collected from sensors installed on the selected components and translated into residual lifespan are the inputs of the DSS. A calendar of maintenance interventions to be performed on each truck belonging to the analysed fleet is obtained. The output minimizes costs related to the remaining steps of the components lifecycle. This last aspect is especially innovative for the automotive area. Previous studies proposed methods for optimising maintenance scheduling through the control of pure maintenance costs (Haghani and Shafahi, 2002), (Safaai et al., 1999) but not considering the entire lifecycle costs connected to the choice of performing or delaying a given kind of maintenance of a precise component. Moreover, in the proposed approach both the availability of each truck (according to mission profiles) and the availability of the maintenance garage are taken into account in order to avoid the definition of fictitious and un-applicable calendars, assuring a reliable result. Some studies (Carnero, 2005), (Swanson, 2001), (Carnero, 2004) propose methodologies for estimating the potential benefits deriving from the application of a certain maintenance approach. However machine tools are the preferred addressed objects of these strategies and their application to the automotive environment seems to be difficult. For this reason a real-life test has been planned comparing already existent methodologies and the proposed tool.

3.1 The new maintenance process

The proposed approach passes through two main modules: a DSS optimising the maintenance on one single truck is the core of the first part of the tool, while an optimisation of the maintenance activities to be performed on an entire fleet of trucks is the aim of the second module.

3.2 Optimising maintenance on one truck

The first module of the DSS is devoted to the optimisation of the maintenance interventions on one single truck. Steps going from data collection from sensors to computation of Life Cycle Residual Cost for a single component are represented in Figure 1.

The new planned maintenance process passes through the following main steps:

- collection of data from sensors
- sensors data elaboration and components lifespan computation
- definition of truck availability
- definition of a maintenance plan for each truck

Already computed residual lifespan for each monitored component are inputs to the here described DSS module. These values derive from the computation of real-time monitored physical data concerning three main components: brakes, air filter and engine oil. These components are already monitored through sensors and some of the gathered data are the following. For engine oil: RPM – load map, fuel consumption, number of engine start-up, oil temperature, water temperature, engine working hours, engine age, boost pressure. For air filter: difference of air pressure between the inlet and outlet side of the filter, RPM, temperature. For brakes: number of braking actions, energy consumption during braking actions, etc.

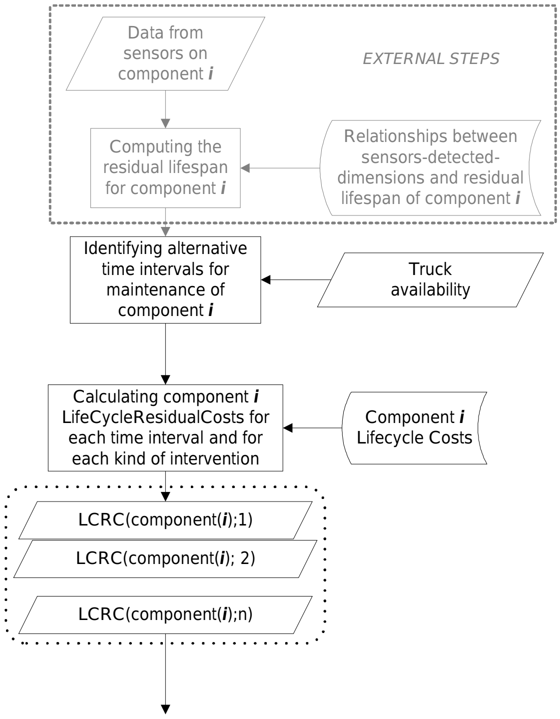

Figure 1: DSS flow chart – part 1

Data collected from sensors are elaborated in order to pass from physical to time, expressing the residual lifespan for each one of the three monitored components. This computation is based on statistical evaluation (Statistical Process Control) taking into account both data collected from past experiences and specific laboratory tests performed on components.

Moreover other data like, for example, costs for performing maintenance, potential costs resulting from delays in interventions, are collected and stored.

Definition of truck availability

The truck owner or the truck manager (from hereon called the user) is here asked to provide the system with time intervals during which the truck is available for maintenance. Maintenance interventions require one-day stop, for almost all kind of maintenance performed (this is an assumption of the algorithm). The user has to communicate such calendar taking into account his needs and implicitly minimizing the missing earnings. Defining the truck availability also allows the user to customize the maintenance service. This term is considered within the optimisation algorithm in order to avoid both components breakdown and too frequent interventions

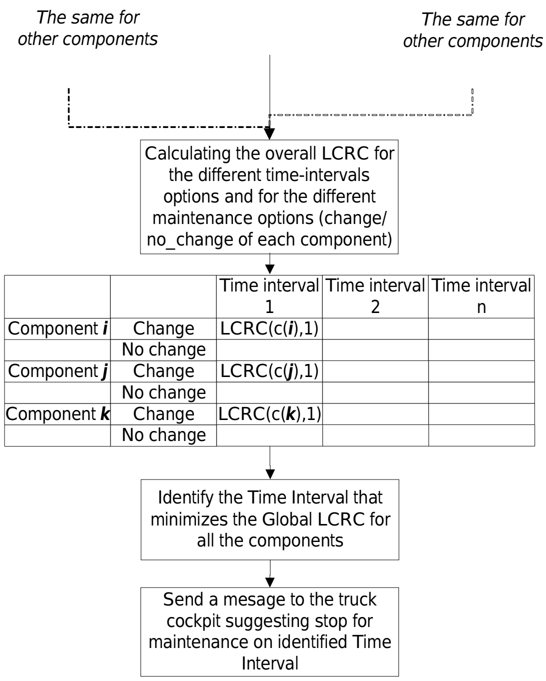

Figure 2: DSS flow chart – part 2

Definition of a maintenance plan for each truck

This step is the "core" of the DSS for a single truck. The system has collected all the needed inputs:

- Residual lifespan for each component
- Time intervals of truck availability
- Pre-scheduled maintenance milestones

The main objective of this step is to identify the "best" time interval for stopping the truck and performing needed maintenance activities and, moreover, to define which kind of maintenance has to be performed on which component. The intervals defined by the user (truck availability) are taken into account as the preferred options, however it may happen that the DSS schedules maintenance intervention outside them if it is necessary to avoid component breakdown and/or too expensive interventions.

Monetary dimensions are taken into account for this optimisation. In particular for each component the following cost entries are considered.

- Costs due to vehicle unavailability
- Costs of intervention (Material, Manpower, Waste disposal)
- Extra costs / problems due to intervention delay (all function of the extra mileage):
    - Vehicle inefficiency
    - Risk of major failure with economical loss
    - Risk of failure with potential hazard for the vehicle / people

It is possible to define a finite number of alternative Component Scenarios (CS) for the maintenance of each component. Each scenario can be defined using 3 dimensions:

- the name of the component [*c*],
- the time window (i.e.: the interval during which the maintenance is planned to be performed, accordingly with truck availability) [*t*],
- The kind of intervention (i.e.: replacement with a new component, retrieval etc.) [*k*].

For each CS a Life Cycle Residual Cost (LCRC) is calculated:= LCRC(*c*, *t*, *k*), expressing the cost of performing maintenance *k* on component *c* in time window *t*.

At this point a set of System Scenarios (SS) can be defined. Two dimensions characterize each SS: time window [T] and kind of maintenance interventions performed on each component [K]. Each K is a three-dimensional array where at position 1, kind of maintenance performed on component 1 is defined; kind of maintenance performed at component 2 is in position 2, etc. (e.g.: rePLAcement of component 1, rePLAcement of component 2 and reTRIeval of component 3 is expressed as: K=[PLA, PLA, TRI]. For each SS, LCRC(T,K) can be computed as follows:

$$LCRC(\hat{T};\hat{K}) = \sum_{t=\hat{T}} \sum_{k_i \equiv \hat{K}[i]} \sum_{c} LCRC(c,t,k_i)$$

$$\mathrm{LCRC}(\hat{\mathrm{T}};\hat{\mathrm{K}}) = \text{Life Cycle Residual Cost for System Scenario } \mathrm{SS}(\hat{\mathrm{T}};\hat{\mathrm{K}})$$

$$\mathrm{t} = \text{time interval}$$

$$\hat{\mathrm{T}} = \text{selected time interval}$$

$$\mathrm{c} = \text{component; } \mathrm{c} \in \{1;2;3\}$$

$$\mathrm{k_i} = \text{kind of maintenance for component i; } \mathrm{k_i} \in \{\mathrm{PLA};\mathrm{TRI}\}$$

$$\hat{\mathrm{K}}[\mathrm{i}] = \text{value of selected kind} - \text{of} - \text{maintenance} - \text{array at position i}$$

As described in Figure 2, Life Cycle Residual Costs for the different components monitored on a single truck are put together and optimisation for the single truck is performed. At this point having the different values of LCRC for each SS, we are able to define the following matrix:

	T_1	T_2	…	T_n
K_1	LCRC(K_1; T_1)	LCRC(K_1; T_2)	…	LCRC(K_1; T_n)
K_2	LCRC(K_2; T_1)	LCRC(K_2; T_2)	…	LCRC(K_2; T_n)
…	…	…	…	…
K_n	LCRC(K_n; T_1)	LCRC(K_n; T_2)	…	LCRC(K_n; T_n)

The System Scenario that minimizes the overall lifecycle residual cost for the truck is identified.

The proposed model is quantitative and monetary-based: the optimization is exclusively performed on estimated cost entries. Other dimensions (e.g.: safety of the truck driver, safety of other people or things, environmental impact, etc.) are considered only performing an economical estimation of the possible events deriving from a delay in performing maintenance on a given component. It is often an ambitious work (e.g.: how to estimate the costs resulting from an accident due to a failure in the brakes? And which is the probability of its occurrence?) and for this reason non-monetary thresholds forcing the algorithm to reject "dangerous", "unsuitable" or too "risky" options have been added (e.g.: imposing a stop when the consumption of a critical component exceeds a pre-defined threshold).

3.3 Optimising maintenance of a fleet of trucks

What described until now is part of the first DSS module. Using the point of view of the fleet manager, however, optimising the maintenance only at the truck level would be a sub-optimal solution. The main goal of the second module of the DSS is to find out an optimal solution at the fleet level.
All the data from the different trucks belonging to a fleet have to be collected in a ground-station computer, in order to simultaneously take into account the different needs and availability of all the trucks. Therefore, data of the different trucks belonging to the same fleet are grouped and optimisation for the fleet is performed. Calendar of interventions is sent to the maintenance crew and to the different trucks Figure 3.
Steps belonging to this second module of the DSS which have been identified till now are:

- Collection of data from the different trucks belonging to the fleet
- Collection of garage availability
- Identification of alternative options and optimisation
- Transmission of results (calendar) to the truck drivers and to the maintenance crew

Collection of data from the trucks
The ground-station computer receives from each truck the matrix described in the previous paragraph. That matrix embodies data on truck availability and on LCRC for each System Scenario. All these matrixes are then stored in the database.
Definition of garage availability
Garage availability is the only missing information, at this point. The fleet manager has to define it, simply conveying how many operators are available for maintenance and when. Future developments of the tool will allow expressing also skills available at a time (e.g.: only component *i* replacement, component *i* replacement and component *j* retrieval, etc.).
Identification of alternatives and optimisation
Inputs of this step are: LCRC for each truck and for each System Scenario, garage availability and other data related to interventions duration, location of the garage, etc.

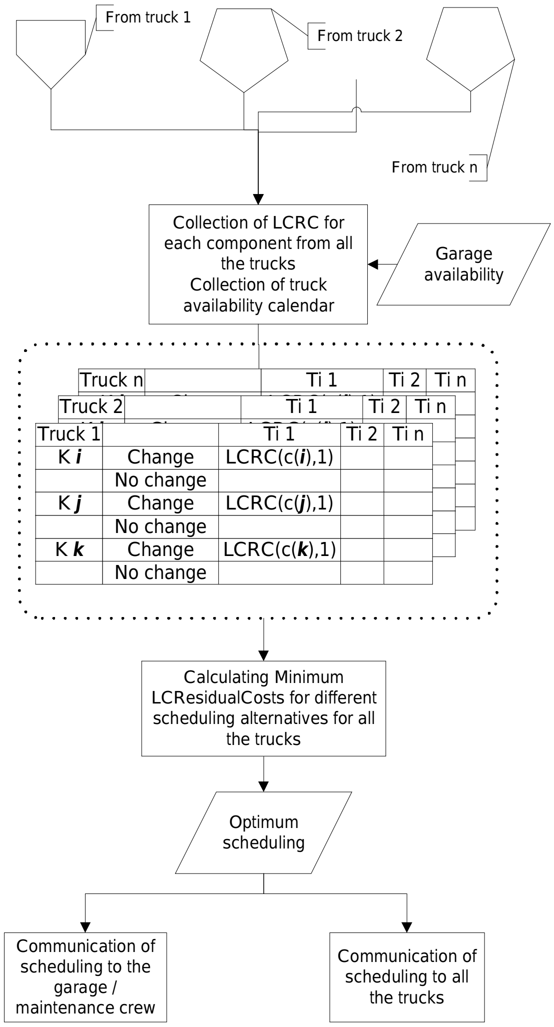

Figure 3: DSS flow chart – part 3
[Ti = Time Interval; K = Component]

Three dimensions now characterize each LCRC:

- T (time interval for performing interventions)
- K (kind of interventions for each component)
- TR (truck)

A LCRC(T;K;TR) is defined.
Also a Fleet Scenario (FS) characterized by two dimensions can be defined:

- K (a matrix representing the kinds of interventions on the three component of each truck);
- T (an array representing the time intervals in which each truck performs above mentioned maintenance interventions)

The output of this step consists of a calendar where dates and kinds of interventions to be performed for each truck are shown.
In order to identify the scheduling of maintenance interventions that minimizes the overall LCRC, the "fleet maintenance management" algorithm will be implemented so that it searches for the optimum Fleet Scenario, taking into account, through a proper set of constraints, maintenance crew availability (in order to avoid the simultaneous stop of a number of trucks exceeding the garage capacity) and trying, when possible, to respect each truck availability.
The design and development of this part of the algorithm is still a work in progress; the description

given above has to be translated into running tools and tested.

Transmission of results

The calendar with the planned interventions on each truck is finally sent to each truck cockpit and to the maintenance crew.

4 CONCLUSIONS

In the design of this DSS, different stakeholders requirements have been taken into consideration, referring to actors that will use (or interact with) the tool in different steps of its lifecycle. The main addressees are in the Middle-of-Life phase: truck drivers/owners, fleet manager and maintenance crew. However, comparing actual performance of monitored components with reliability and features supposed at the beginning of their life provides value-adding information also to the design department of the truck manufacturer (Beginning of Life phase) and, finally, to End of Life actors devoted to the re-usage, retrieval and dismantling of the components. The here-described approach is still at the developmental phase and the underlying project is on going. Benefits deriving from the adoption of this tool will be weighed up and compared to already existent solution through proper on-the-field inspections. The consideration of Residual Lifecycle cost in the DSS permits to have a wider vision on the product and on the services connected to the product itself. The validation of the proposed algorithm is planned to be carried out on a fleet of trucks. Present preventive procedures are going to be compared to the proposed condition-based policies in terms of costs resulting in a selected time horizon, focussing on the maintenance of the three monitored components.

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