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Transportation Research Procedia 14 (2016) 635 – 644

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

Novel efficient technologies in Europe for axle bearing condition monitoring – the MAXBE project

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Abstract

Axle bearing damage with possible catastrophic failures can cause severe disruptions or even dangerous derailments, potentially causing loss of human life and leading to significant costs for railway infrastructure managers and rolling stock operators. Consequently the axle bearing damage process has safety and economic implications on the exploitation of railways systems. Therefore it has been the object of intense attention by railway authorities as proved by the selection of this topic by the European Commission in calls for research proposals. The MAXBE Project (http://www.maxbeproject.eu/), a EU-funded project, appears in this context and its main goal is to develop and to demonstrate innovative and efficient technologies which can be used for the onboard and wayside condition monitoring of axle bearings. The MAXBE (interoperable monitoring, diagnosis and

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Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.313

maintenance strategies for axle bearings) project focuses on detecting axle bearing failure modes at an early stage by combining new and existing monitoring techniques and on characterizing the axle bearing degradation process. The consortium for the MAXBE project comprises 18 partners from 8 member states, representing operators, railway administrations, axle bearing manufactures, key players in the railway community and experts in the field of monitoring, maintenance and rolling stock. The University of Porto is coordinating this research project that kicked-off in November 2012 and it is completed on October 2015.
Both on-board and wayside systems are explored in the project since there is a need for defining the requirement for the onboard equipment and the range of working temperatures of the axle bearing for the wayside systems. The developed monitoring systems consider strain gauges, high frequency accelerometers, temperature sensors and acoustic emission. To get a robust technology to support the decision making of the responsible stakeholders synchronized measurements from onboard and wayside monitoring systems are integrated into a platform. Also extensive laboratory tests were performed to correlate the in situ measurements to the status of the axle bearing life. With the MAXBE project concept it will be possible: to contribute to detect at an early stage axle bearing failures; to create conditions for the operational and technical integration of axle bearing monitoring and maintenance in different European railway networks; to contribute to the standardization of the requirements for the axle bearing monitoring, diagnosis and maintenance. Demonstration of the developed condition monitoring systems was performed in Portugal in the Northern Railway Line with freight and passenger traffic with a maximum speed of 220 km/h, in Belgium in a tram line and in the UK. Still within the project, a tool for optimal maintenance scheduling and a smart diagnostic tool were developed.
This paper presents a synthesis of the most relevant results attained in the project. The successful of the project and the developed solutions have positive impact on the reliability, availability, maintainability and safety of rolling stock and infrastructure with main focus on the axle bearing health.

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Keywords: axle bearings; condition monitoring system; diagnosis; condition-based maintenance

1. Introduction

The safety of rolling stock and the economic implications of rolling stock maintenance have been of significant concern to the railway industry. In the last few years the maintenance strategy paradigm is significantly changing and the longstanding preventive time based maintenance is being progressively replaced by condition based maintenance. Also the early diagnosis of the rolling stock condition will allow the improvement of the definition of the maintenance strategies for railway vehicles. Condition monitoring technologies offer to the railway operators means to increase reliability and safety. By an earlier detection of potential failures, the railway operators can better plan maintenance actions contributing to achieve financial savings (MAXBE, 2012).

The axle bearing damage process and the consequent failures can cause severe delays or even dangerous derailments implicating human lives prejudice and significant costs for railway managers and operators. The usual causes for axle bearing failures are: the ageing and the deterioration of grease; the oil separation from the grease structure; the particle contamination of the lubricant grease due to wear from components; the external particle contamination due to damaged seals and out of balance axle loads. When the axle bearing temperature rises, it can be indicative of possible failure, loss of internal kinematics, lack of lubrication and overloading, factors that can dramatically reduce bearing life (MAXBE, 2012).

In railways, the axle bearings condition monitoring can be made directly (on-board) or indirectly (on-track and on-laboratory). Regarding the wayside condition monitoring, hot axle box detectors are the most common track side monitoring systems and are used for the detection of faulty axle bearings in-service. However, these systems cannot detect damage in early stage, because when the alarm temperature is registered the axle bearing is already in an advanced state of degradation. Also, with this type of monitoring systems, overheated bearings may not be detected and false alarms can be triggered during operational conditions. Therefore, more accurate methods for the bearing health monitoring need to be developed considering vibration and acoustic analysis. But these techniques are complex and their application to the railway industry is limited. The on-board condition monitoring systems implies that different types of sensors, generally including temperature, vibration and/or acoustic emission sensors, are installed directly in the axle box, consequently, these systems are more likely to detect an axle bearing fault, especially at an early stage of evolution. But on-board systems may have technical limitations related with power supply, communication system and adaptability of the systems to different type of trains as well as data processing tools that can improve the reliability and effectiveness of these systems.

2. Description of the MAXBE project

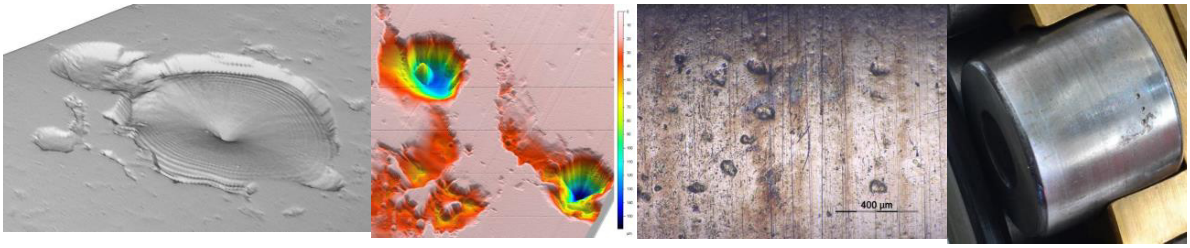
The MAXBE project focuses on detecting the axle bearing degradation process. With this project it will be possible: to contribute for detecting at an early stage axle bearing failures; to create conditions for the operational and technical integration of axle bearing monitoring and maintenance in different European railway networks; diagnosis and maintenance (MAXBE, 2012). To accomplish the MAXBE project aims, a consortium including 18 partners from 8 European member states was established: University of Porto (Portugal); REFER (Portugal); ASTS (Italy); UNIGE (Italy); IVE (Germany); COMSA (Spain); University College Cork (Ireland); EVOLEO (Portugal); Nuevas Estrategias de Mantenimiento NEM (Spain); MERMEC (Italy); SKF (Spain); Instituto Superior Técnico (Portugal); Dynamics, Structures and Systems International (Belgium); Vlaamse Vervoersmaatschappij De Lijn (Belgium); NOMADTech (Portugal), I-moss (Belgium); KRESTOS (UK); University of Birmingham (UK).

The project, financially supported by the European Commission through FP7, kicked-off in November 2012 and it is completed in October 2015. To accomplish the strategic and the technological objectives, the MAXBE project comprises nine Work Packages in which it is proposed to develop and analyze the results from both on-board and track side systems together with the results from the laboratory tests based on several indicators identified for early detection of the axle bearing condition, to develop an integration platform for the different types of monitoring systems and to define important correlation laws between the outputs of each system that will be integrated in the maintenance models for axle bearings. The detailed description of the Work Packages can be found in the website of the project: www.maxbeproject.eu.

3. Main project results and findings

3.1. Laboratory tests

Aiming the assessment of the real bearing failures and of lubricant degradation during and after service, the analysis of bearing/grease reliability and maintenance data that can be used in RAMS models and also the analysis of the correlation between real bearing operating parameters and model prediction, related to temperature, vibration, dynamic loading and grease ageing, several analysis were performed in axle bearings from PCC Antwerpen unit (tram that circulates in Antwerp) and UME 3400 unit (Urban train of Oporto). The study comprised Ferrography analysis, viscosity analysis and surface analysis (visual inspection, microscopic surface analysis and roughness measurements), as presented in Fig. 1 (MAXBE, 2013a).



(a) (b) (c) (d)

Fig. 1. (a), (b) Roughness measurement of the damage observed in a roller (crater); (c) Microscopic surface analysis; (d) Visual inspections.

Regarding the rolling bearing surface analysis, two used axle tapper roller bearings removed from a PCC Antwerpen unit were analysed in order to identify different types of surface damage in the inner raceways, outer raceways and rollers that could lead to potential bearing failure. There were identified several types of surface damage such as indentations, craters, cracks and sizable particles (approx. 80 μm) on the verge of being released due to wear.

In order to assess the mechanisms behind the friction torque and power loss of the rolling bearings under oil or grease lubrication, rolling bearing tests were performed with a modified Four-Ball Machine where the four-ball arrangement was substituted by a rolling bearing assembly developed to test several rolling bearings and measure the friction torque and the operating temperature in several different points. The friction torque was measured with a piezoelectric torque cell and the temperature measurements were performed through thermocouples installed at strategic locations. Both types of axle bearings (PCC Antwerp and UME3400) were analyzed considering the specific load conditions and lubricants. As expected, the operating temperature increases with the increase of speed and load, being the speed the most relevant parameter responsible for the temperature increase.

Vibration analysis in a faultless axle bearing from the UME3400 unit was also performed considering two different load conditions: unloaded and loaded using accelerometers and a dynamic signal analyzer. The testing was carried out for the shaft running at approximately 264 rpm (4.4 Hz). The vibration signals were processed by a FFT conventional approach in the frequency domain were all vibration components including: bearing vibration, unbalance and misalignment were analyzed.

3.2. On-board monitoring systems

The developed on-board monitoring system, composed by a set of sensors installed in the axle box, a GPS, and an acquisition system connected with a data processor unit, measures two aspects of the axle bearing behavior: the temperature and the vibration levels in three distinct directions (MAXBE, 2013b, MAXBE, 2015a). A general overview of the on-board monitoring system configuration is presented in Fig. 2 The acquisition system receives the raw data from the sensors and stores it into an on-board CPU. The data management, such as the correlation of the data from the sensors with the GPS information, the data processing, is also performed in the on-board unit. A communication module allows the access to the raw and processed data, enables the remote access to the system and monitors the state of the equipment.

The raw data or the processed data converted into key performance indicators (KPIs) are then transferred to an on-shore server, which enables the access of the data in the data fusion algorithms and feeds the smart diagnostic tool. Considering the benefits of the correlation of on-board and wayside measurements, a radio-frequency identification system (RFID) is considered and installed in Alfa-Pendular trains crossing the Estarreja test site, as part of testing. The RFID system is composed by the tags installed in the trains which send a signal to the reader system when the train crosses the wayside monitoring system.

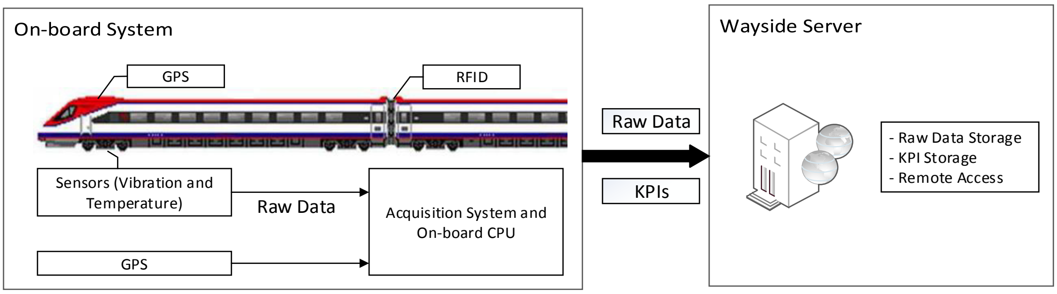
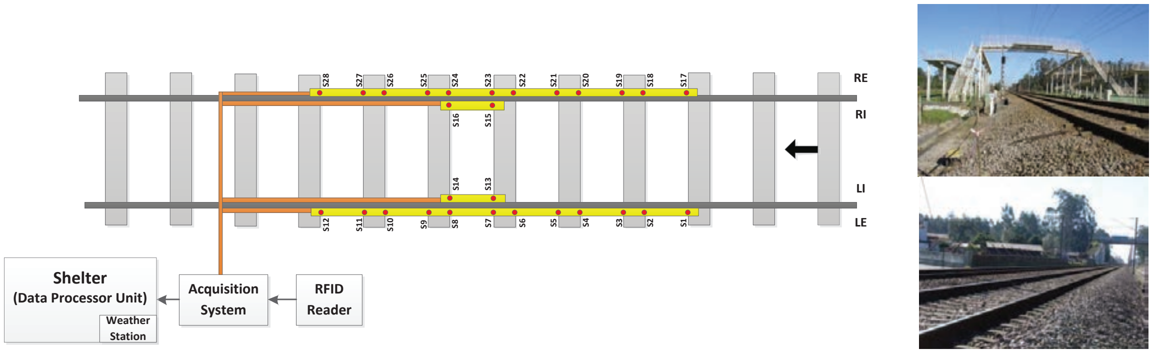


Fig. 2. General overview of the on-board monitoring system in Alfa-Pendular train (CPA4000).

3.3. Wayside monitoring systems

3.3.1. Vibration monitoring system

The vibration wayside monitoring system is installed in the Portuguese Northern Railway Line at Estarreja and it is composed by a set of sensors (strain gauges) installed in the track, connected to an acquisition module and to a data processor module (MAXBE, 2014; MAXBE, 2015b). Sensors are installed at the web of rail along an equivalent wheel perimeter length. The system has a total of 28 strain gauges, divided in groups: 12 sensors installed in the external side of each rail and 2 sensors in the internal side of each rail. The installation scheme is presented in Fig. 3.



(a) (b)

Fig. 3. Wayside system: (a) installation scheme; (b) location of Estarreja test site.

The sensors are protected against the railway adverse environment, with dust, ballast, water and all the heavy maintenance activities performed in this type of infrastructure with a robust mechanical system. The cables connecting the sensors to the acquisition system are in underground ducts in order to ensure the safety and the durability of the system considering the maintenance activities.

In Fig. 4, the acquisition system, the data processor unit and the communication system installed in a cabinet in the side of the track is shown, as well as the installation of the sensors in the track.

Fig. 4. Wayside system in Portugal: data processor unit and system installation in the track.

The raw data acquired from the sensors installed in the track is processed in the data processor unit through the data processing algorithms briefly described in Fig. 5, that includes information from the infrastructure manager data base (for instance general information about the trains – geometry, references). The settings of the data processor unit, as the definition of the KPIs (CEN, 2012), trending limits and sensitivity can be remotely defined/modified.

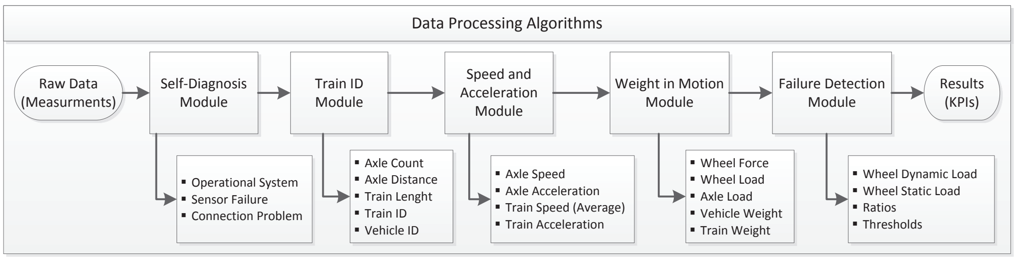


Fig. 5. Data processing algorithms.

3.3.2. High Frequency Vibration monitoring system for Light-Rail Vehicle axle bearing monitoring

A high-frequency vibration-based axle bearing fault detection system jointly developed by De Lijn, D2S, and I-moss is installed in the Antwerp depot of De Lijn, the Flemish public transportation company. The system is installed on the exit track of the facility, monitoring all vehicles exiting from the depot onto the Antwerp tram network. Fig. 6 shows some pictures of the wayside installation in Antwerp (MAXBE, 2015b).

The installation on an LRV (Light Rail Vehicle) network has some specific characteristics: embedded track, car and bus traffic, speed and weights different from mainline, etc. The hardware setup chosen in the De Lijn demonstrator takes these requirements into account.

The complete system is composed of 8 high frequency accelerometers, mounted on the rail feet, field side. The accelerometers are connected to a processing unit, located in the vicinity of the accelerometer in a weatherproof casing. The accelerometers are specified for high frequency vibration measurement and have a sensitivity of 10 mV/g.A mechanical protection system is installed over the accelerometers for protection against moisture, dirt and EMC and isolating them from external vibration sources. Spacing between the accelerometers is 52 cm, approximately one fourth of the wheel circumference.

The processing unit is composed of signal conditioning cards, a data acquisition card and an embedded computer. The system also features a 3G connection to allow data upload to a centralized measurement database. The in-house built signal conditioning cards have been tuned for high frequency signals, measuring vibration signatures of up to 40 kHz.

All vehicles are identified by a unique number. A magnetic loop reads the vehicle number. As a second identification system, this prototype also contains a high-definition, high-speed camera providing a picture of each vehicle, that allows to decode its identification number optically with OCR software (Optical Character Recognition). This solution is promising for mainline installation.

Each wheel’s high-frequency vibration is measured by 4 sensors sampled at 80 kHz. This time signal is enveloped and on the spectra a peak-to-average norm is taken as a basis for anomaly alerting. Based on the central measurement database, also trending is possible.

The installation has been in continuous operation for more than two years now and has proven to be robust in a very adverse environment, with braking sand and busses passing from the De Lijn depot. This robustness of the installation is a major advantage of this type of sensors over other methods of detection.

Fig. 6. Wayside axle bearing monitoring system for Light Rail Vehicle.

3.4. Wayside and On-board interface software

In the last years, railway and metro transportation systems have been characterized by a continuous growth in the traffic volume, speed and axle-load (Islam et al., 2015). For this purpose, in the context of condition-based maintenance, the application of innovative monitoring and diagnostics technologies plays a key role (Mirabad, 1996; Flammini, 2010; Zhou et al., 2014); these advanced systems are used for the inspection and the fault detection of both rolling stock and infrastructure components in order to increase the safety and reliability levels of the railway operations and to reduce the maintenance costs. Due to the need of high performance standards of these kind of instrumentations (such as reliability, accuracy, etc.) and the incompleteness of information coming from each single sensor about the asset status and related degradation processes, it is extremely important to study and to deploy Data Fusion methodologies able to correlate data coming both from the wayside train monitoring systems (WTMSs), and from the on-board train monitoring systems (OTMSs). These kind of systems enable monitoring the same phenomena and potential issues from different perspectives; although they are autonomously able to raise warnings and alarms, it is possible to exploit their complete potential only by fusing their outputs (Hall and Llinas, 1997). “Data Fusion” targets the merging of heterogeneous data so to extract high-level patterns: the final purpose is to help decision makers taking the best possible decisions; the latter ones span from raising alarms and stopping trains, if necessary, down to maintenance planning, limiting disruptions to the service offered to the customers (JDL, 1991).

In the context of railway asset management, one of the most innovative research areas is the multi-sensor Data Fusion; for this reasons, an innovative software Integration Platform based on Data Fusion approach for axle bearing condition monitoring has been developed. It has been performed by three main modules, i.e. a Data Fusion Application (DFA), a System Integrator (SI) and a visualization system referred as Human Machine Interface (HMI), which are interconnected by interfaces that allow communications through messages in eXtensible Markup Language (XML) format, as shown in Fig. 7.

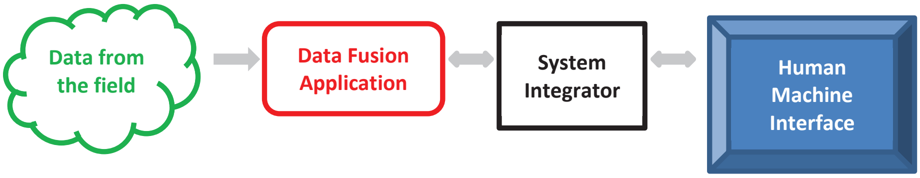


Fig. 7. MAXBE Integration Platform – architecture.

The DFA gathers all the data at sensor level and combines them by subsequent processing; it extracts high-level patterns through a probabilistic Bayesian methodology which is able to exploit data to output both: 1) an accurate estimation of the occurrence probability of current and/or incoming potential failures; 2) a confidence interval of this risk, useful for decision makers to assess the reliability of the extracted pattern.

The SI manages the interaction between different software technologies in order to integrate every module into a single system capable of collecting data, performing the data fusion in order to extract new information and visualizing the results of this process in a user-friendly manner through the HMI. It updates asset related information disseminated to all the parts of the system as soon as new data is available or new data fusion processing has been completed, so that, for example, the visualization system always shows the most updated information possible.

The HMI (shown in Fig. 8) is a web-based visualisation system that allows visualising data and information generated by the DFA, such as potential alarms, in a user-friendly graphical way. The most important characteristics of such an interface are the clearance, the simplicity and ease of use. The visualization system includes pop-out elements that highlight the presence of dangerous situations, and consequently it is able to explore data related to the particular phenomena in order to have, if requested, a more precise view of the situation under examination.

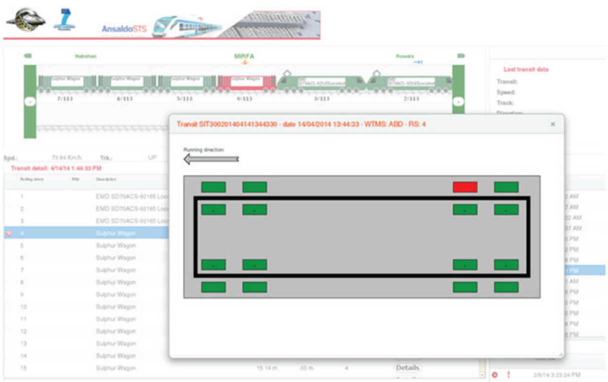


Fig. 8. Example of HMI.

The entire software Integration Platform based on Data Fusion approach has been inspired by the JDL generic model (JDL, 1991; Llinas and Hall, 1994), of which it represents a possible implementation for condition monitoring applications.

The system has been able to perform the following functionalities:

- to collect and store measurements and data coming from the WTMSs and OTMSs related to the axle bearing functional conditions;
- to correlate and process these data through a Data Fusion Application (DFA) in order to provide useful aggregated information about the status of each axle bearing under examination;
- to visualize through a Human Machine Interface (HMI) events (such as defects, anomalies, failures, etc.) related to axle bearings of different kinds of trains (passenger, freight, high speed, etc.);
- to highlight critical asset condition in order to allow maintenance operators to take proper actions, support decision making by giving a synthetic final alarm level and an associated value ("Veracity") as the likelihood of the generated alarm level.

The tests and validation of the DFA, and consequently of the algorithm, has been performed and completed with laboratory tests, showing that the system gives satisfying results and fulfils all the requirements. The results show benefits in terms of maintenance costs reduction, risk management and safety, and the system proves to have a positive impact all over the railways systems. Future steps include the realization of a real demonstrator by collecting and processing real data coming from the test sites in Estarreja (Portugal) and in Antwerp (Belgium), officially scheduled for the final phase of the MAXBE project (MAXBE, 2015c).

3.5. Tool for optimal physical distribution of the monitoring systems

The monitoring systems are expensive and the investment and the maintenance of this type of systems have to be taken into account by the Infrastructure Managers. Moreover, since there is no available tool to help deciding the distribution layout of the monitoring systems in a railway network within the MAXBE project a tool to identify the optimized physical distribution of the condition monitoring systems and its monitoring interval rates is developed.

The tool considers historical and statistical data of the railway network and particularly data from the railway line in analysis. The developed tool takes into account the risk associated to certain indicators and the importance assigned to each one of the pre-defined indicators, in order to be able to identify the most critical aspects regarding the axle bearing failure in a railway network.

Although within MAXBE project, several wayside systems using different types of technology were developed, the most widespread system already existing in several railway networks is still the Hot Axle Box Detectors (HABD) and therefore, the guidelines and requirements already available are for this type of devices. In this context, the developed software tool considers the requirements for the installation of HABD, taking into account particularly, the different criterion considered in Portugal, United Kingdom, Germany, Belgium and France. The tool is a decision-aid support system, which assists the infrastructure manager in the decision of the physical distribution of Wayside Diagnostic Devices (WDD) within the railway network considering their own criteria regarding safety, quality of service and also taking into account the main guidelines for the installation of these devices in the railway network of each country.

The tool is available in excel format programmed with Visual Basic and therefore is user-friendly, easy to implement and very flexible in order to be adapted to the end-users needs. At the end, the tool is able to suggest the most adequate places to install a wayside monitoring system, by weighting the several risk assessment indicators defined in the software tool (MAXBE, 2015d).

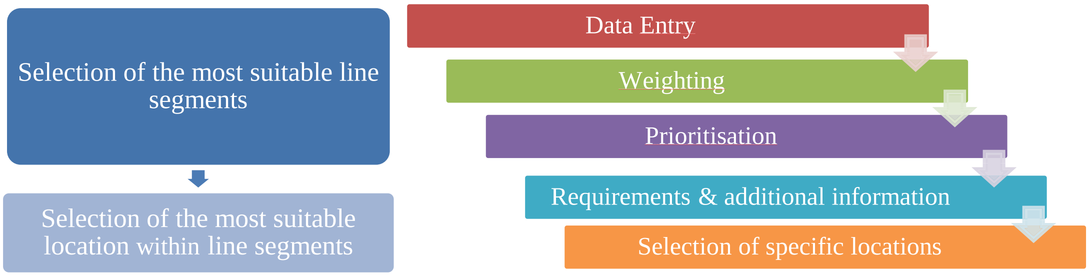


Fig. 9. Methodology of the software tool.

3.6. Maintenance tool

The increase in condition-based maintenance (CBM) of assets such as axle bearings should have a number of positive benefits for the train operating company, such as a reduction in in-service failures, a reduction in maintenance costs as maintenance for certain components can be moved from periodic planned maintenance to condition-based, increase in the lifetime of the assets, etc. However, this also creates certain challenges for the maintenance operating company, as there is greater uncertainty regarding what depot resources will be needed for performing maintenance and when they will be needed. Indeed there is already significant uncertainty regarding the duration of planned maintenance exams (Snoek, 2014), as the exact maintenance requirements are often only known after performing a manual inspection in the depot.

The maintenance schedule optimizer software tool that has been developed within the MAXBE project was implemented such that it can be deployed in a number of different maintenance depot scenarios, e.g. single versus multiple fleets, passenger versus freight fleets, with or without overtime staff, periodic maintenance with kilometric or time-based limits, etc (MAXBE, 2015e). The tool considers time-variable fleet demand profiles, periodic exam due dates, resource/staff depot capacity constraints at an hourly level, over a fixed rolling horizon; while also incorporating proactive and reactive methods for handling the uncertainty inherent in the maintenance scheduling problem.

The problem is solved using dedicated Constraint Programming methods, and the optimizer is implemented in Python in Google's or-tools solver, which is a free, open-source set of operations research tools. All accompanying software are implemented in Python, including a graphical user interface for the solver and a tool for automated distribution fitting of maintenance exam durations based on historical data, and are open-source and freely available. While the tool can primarily be used for scheduling of daily activities in a rolling horizon capacity, it can also be used to identify bottlenecks in the depot specification. Cost-analysis of alternative depot setups (e.g. increasing or decreasing tracks/resources, altering staff shifts) can then be performed through simulation experiments using the tool.

4. Conclusions

The axle bearing damage process and the consequent failures can cause severe delays or even dangerous derailments implicating human lives prejudice and significant costs for railway managers and operators. Therefore, reliable and interoperable monitoring, diagnosis and maintenance strategies for axle bearings are needed. The MAXBE project, a EU-funded project, appears in this context and it focuses on detecting axle bearing failure modes at an early stage by combining new with existing monitoring techniques, characterizing the axle bearing degradation process and defining condition-based maintenance strategy for axle bearings. This paper presents a synthesis of the most relevant results/achievement attained in the project.

Acknowledgements

The authors wish to acknowledge to the European Commission for funding this research within the 7th Framework Programme (MAXBE/314408/FP7-SST-2012-RTD-1, Interoperable Monitoring, Diagnosis and Maintenance Strategies for Axle Bearings).

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