Critical components selection for a Prognostics and Health Management system design: an application to an overhead contact

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Abstract

In recent years, improving quality of rail services by increasing reliability and availability; saving energy; cutting the costs of infrastructure and rolling stock maintenance became a central concern in the railway industry. Furthermore, considerable research efforts have been devoted to develop monitoring and health management solutions for the rail transportation systems. Streaming data from trains, infrastructure and signaling systems became a key subject for an implementation of a predictive maintenance. Prognostics and Health Management (PHM) is an approach that aims to support a predictive maintenance program by affording solutions for an accurate monitoring of the industrial equipment; detection and diagnostics of abnormal behavior or failures; estimating the Remaining Useful Life (RUL) of a degrading asset which allows maintainers to plan the maintenance tasks depending on the real health state of the equipment. Developing a PHM solution necessitate multiple steps. In component based prognostics, the first step to develop a PHM system is to identify critical components. This paper emphasizes on the critical components selection step. It presents a methodology to identify the critical components for the design of a PHM solution. The proposed methodology is based on objectives definition for PHM and is applied to an Overhead Contact System (OCS) to show its effectiveness.

1. Introduction

The railway industry is aiming to develop more efficient and intelligent systems which can respond to the increasing need for mobility and time issues. In the last decade this industry showed a growing interest focused on maintenance techniques and monitoring systems for the rolling stocks, the signaling systems and the infrastructure. In this context the current collection system is a key issue in modern railway industry. In fact, a degraded or even damaged components of the Overhead Contact System (OCS) or the current collectors can lead to train delays, infrastructure and rolling stock damages or even electrocution of passengers. In 2009 for example, catenary incidents generated more than 2500 hours of delay for 150 millions of euros of losses for the SNCF (Massat, 2007).

Within this framework, an implementation of an adapted maintenance policy to manage the operability of the asset become a crucial task for competitiveness. Regarding the security, reliability and availability requirements of systems such as OCS and pantograph, efforts are made to implement Condition-Based Maintenance (CBM) and preventive maintenance for the railway infrastructure using inspection trains and diagnostics solutions. The CBM is a maintenance program in which the tasks are planned regarding the health status of the physical asset. Set up properly and effectively implemented, it can significantly reduce maintenance costs by replacing the number of unnecessary planned operations by necessary ones, and ensure an optimization of service by operating only when the current condition of the asset is critical (Jardine, Lin, & Banjevic, 2006). In the last decades the techniques used in the CBM and the predictive maintenance area evolved by the rise of new technologies of sensors, data storage, data processing and data streaming, this evolution led to the emergence of the field of the Prognostics and Health Management (PHM).

The PHM can be defined as a system engineering discipline which provide key processes, technologies and techniques to achieve an accurate monitoring of an industrial equipment; asses the current state of an equipment and realize detection and diagnostics of abnormal behavior or failures; estimate the future health state of a degrading asset by calculating the Remaining Useful Life (RUL) and an associated confidence interval. This is a discipline which enable the CBM and the predictive maintenance.

Basically, the prognostics relies to state detection, diagnostics and prognostics activities, and health management include activities such autonomic logistics based on diagnostics and prognostics results.

Implementing a PHM solution requires a significant levels of knowledge in many domains in order to select the adapted sensors, data acquisition, diagnostics and prognostics algorithms and software/hardware solutions to reach each capability. Several solutions were developed in the field of PHM, however there is no systematic method to design and deploy a PHM system and it depends on several parameters such as prognostic requirements, available knowledge of systems and engineering resources. Nevertheless, the development of a PHM system relies generally on the following element (Uckun, Goebel, & Lucas, 2008):

- Define business case for the prognostic form system requirements
- Identification of the critical component of the supervised equipment
- Define the physical parameters to monitor
- Develop or select associated sensors and acquisition systems.
- Generate data from a virtual simulator, a test bench or from an appropriate samples number of operating component in order to depending on the selected approach and process data
- Select the most appropriate approach for state detection, diagnostics and prognostics regarding the available means.
- Integrate the developed hardware and software solutions to the final system.
- Validation and verification of the developed hardware and software solution.

In general, the identification of the critical components is the first step for the implementation a PHM approach. It aims to determine which component or sub-system contribute the most to the degradation and affect the performance of the system in term of availability, reliability and downtime costs. Then the most critical failure modes are assessed to define the most appropriate and mature diagnostic and prognostic technologies and the appropriate monitoring technology solution.

The assessment of critical components or critical sub-systems is done using component failure data and operating data to assess the reliability of the system. However, in certain cases failure data are not effortlessly available, for example for linear assets such as railway infrastructure, so other methods must be used to assess the criticality of the asset. Moreover, the selected critical components must comply with the relevant requirements defined for the prognostics and the diagnostics functions. To this aim, a procedure must be set up to determine the critical components and critical failure modes regarding the aim of a PHM development.

In this paper we propose a systematic approach for the criticality determination of systems regarding a PHM system development. The section 2 present the different methodologies to determine critical component in reliability. The section 3 aims to propose an approach to assess the criticality of a system regarding a PHM implementation objectives. Then the methodology is applied to the OCS which have a great influence on the operability of the railway system.

2. Review on criticality determination and PHM

Classical diagnostics approaches use system control parameter and performance data to deduce and detect a faulty state of a sub-system or a component. However, with the development of systems complexity, detect faulty components or failures become increasingly complicated and necessitated the extraction of specific features using monitoring systems. In this context, we can distinguish two type of monitoring levels for the PHM implementation: system level monitoring which aims to get system performance and control data, and the component level monitoring which aims to supervise the behavior of critical components (Mosallam, Medjaher, & Zerhouni, 2015). In this way, the identification of critical components is a key task for a PHM system deployment.

Traditionally, one way to define the critical components of a system is by conducting an analysis of system dependability. The dependability of a system is assessed using an evaluation of its attributes such as availability, reliability, safety, integrity and maintainability (Avizienis, Laprie, Randell, & Landwehr, 2004). There are several techniques to assess the reliability of a system depending on the available data and the context. These techniques can be classified into two main groups, namely the qualitative and the quantitative approaches.

The qualitative and semi-qualitative approaches rely to experts' judgment of the available data to identify and evaluate the potential failures to make a reasonable judgment of risks. These techniques can be decision or experience based and provide qualitative evaluation of the risk such as low, medium and high. Qualitative approach is usually performed using techniques such as Checklist, Failure Mode and Effects [Criticality] Analysis (FMEA/FMECA), Preliminary Hazard Analysis PHA, Hazard and Operability Study (HAZOP).

The quantitative approaches can be probabilistic or deterministic. These approaches use statistical methods to estimate measures such as failure rate, mean time to failure (MTTF), Mean time between failures (MTBF), etc. to evaluate a reliability of a system. The most common used techniques are Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). Moreover, the different approaches can be combined for system reliability and risk analysis.

In the context of PHM, the FMEA and its extensions FMECA and FMMEA (Mathew, Das, Rossenberger, & Pecht, 2008) techniques are often used to assess the criticality of the system and define what prognostics can be done for the system regarding the components.

3. Proposed approach

The deployment of a PHM system for a CBM program can insure mainly objectives such as: increasing service reliability; increasing system availability; and decreasing maintenance costs. In the proposed methodology, the identification of the critical components is achieved regarding the 3 objectives cited above for a CBM program implementation. In this framework the goal is to define for each objective the most critical components, as depicted in the following chart:

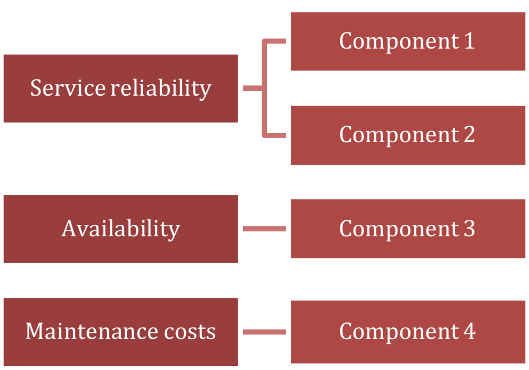

Figure 1. Select component regarding to PHM objectives

Thereafter, the identified critical component are ranked to select the most critical ones for the entire system and their failure modes are studied to select and identify the mature technology for sensors, monitoring, and data acquisition.

3.1. Identify components with high impact on service reliability

Components with a high failure rate can seriously affect service reliability. Insuring monitoring and predictive solutions can help to decrease the occurrence of these failures. In the context of the railway infrastructure this can be achieved by analyzing the most impacting components for incidents and failures; using FMEA analysis; FTA; or other system reliability assessment approaches.

3.2. Identify components affecting the most maintenance and downtime costs

A PHM system can considerably reduce the life cycle cost (LCC) of a monitored system. Indeed, a monitoring system can reduce regular inspection costs by replacing some unnecessary tasks by necessary ones and plan maintenance tasks regarding the current and the future state of the system which can help to reduce spare parts costs and logistics. In addition, setting up a continuous monitoring and a diagnostic solution can help to identify accurately and quickly the failed components which allows reducing costs due to downtime.

Consequently, the components which affect the most maintenance costs and downtime costs are identified in this step aiming a more efficient deployment of a PHM solution.

3.3. Identify components which affect the most system availability

To increase availability, the goal is to identify the component which have the most affecting failures. In other word, this step is dedicated to select the components which cause the most downtime per occurrence and the components with a high frequency of failure. An example of an identification methodology for critical component regarding their impact on system availability is proposed in (Wang & Nee, 2009). It is based on a four quadrant chart which illustrate the frequency rates of components failure vs. the average downtime associated.

3.4. Decision table

After reviewing the most impacting components for maintenance costs, service reliability and system availability. A score is attributed to each component according to its criticality for an objective. Three indexes are defined, index for service reliability criticality (ISR), index for maintenance costs criticality (IMC) and an index for availability impact (IA). Four scores are defined for each index; 0 for the component which have no impact for the defined objective; 1 for a low criticality regarding the defined objective; 2 for medium criticality and 3 for a high criticality. Thereafter, a criticality index (CI) is calculated for each component in order to rank them. An illustration of the decision table is presented below:

Table 1. Decision table for critical components ranking.

Components	Service Reliability (ISR)	Maintenance costs (IMC)	Availability (IA)	CI
Component 1	2	3	2	
Component 2	3	1	1	
Component 3	2	2	3	
…	…		…	
Component n	1	3	1	

Then, a Criticality Index (CI) is calculated for each component (k), as follows:

$$CI_k = ISR + IMC + IA$$

For example, a component which have no impact for Service reliability, a medium criticality for the maintenance costs and a high criticality for the system availability will have a critical index value of: $CI = 0 + 2 + 3 = 5$

3.5. Targets and monitoring parameters identification

After the identification of the critical components, the failure modes and failure mechanisms of each component are reviewed. Then targets are defined for each failure mode or failure mechanism. The targets can be the selection of sensors, acquisition system, or selection of a mature processes for diagnostics and prognostics.

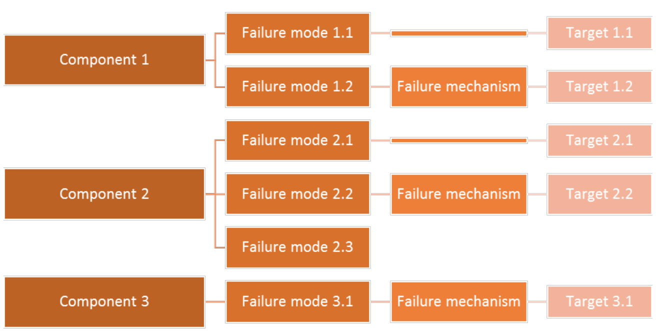

Figure 2. Monitoring parameters selection procedure

The figure presented above, summarize the procedure for the selection and the identification of the PHM system solutions through targets.

4. Case of study the OCS

The purpose of this part is to study the criticality of the OCS system in order to implement a PHM solution for a CBM program. The data used are mostly gathered from literature information, infrastructure manager sources and Alstom's data. The proposed method is applied in the subsequent steps to the Overhead Contact System.

4.1. The OCS system and data

4.1.1. OCS system

Basically, the OCS system is an assembly of cables carrying necessary electrical energy to the trains. It is composed of simple conception components such as cables and pulleys. However, the dimensioning of each component requires relatively complex calculations to obtain a very accurate geometry. Furthermore, the procedures for mounting and adjustment of a catenary are result of decades of experience.

There are multiple types of catenaries conceptions depending on the type of the carried current, train desired speed and environmental constraints. The Figure 3 shows an AC OCS system used for high speeds line, it is composed of several elements; the contact wire which is in charge to provide the current to the trains with its interaction with the pantograph system; the messenger wire which carry the contact wire and ensure its "flatness" using the droppers; cantilevers which

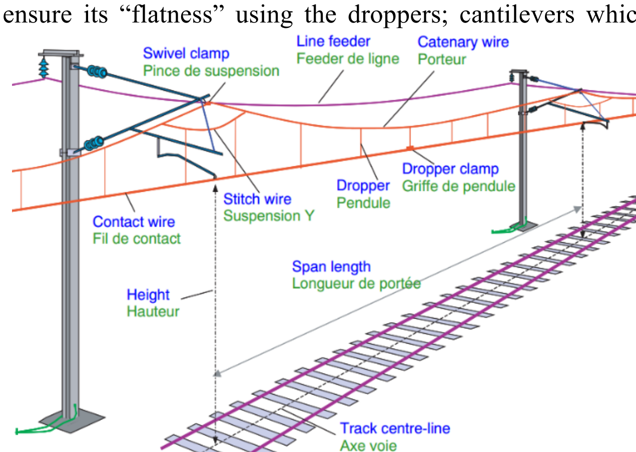

Figure 3. A span of an AC Overhead Contact System

support the messenger and contact wire and allows the poles to carry them. This span is repeated to define a section. The sections are spanned along the railway infrastructure.

4.2. Identification of the OCS components with high impact on reliability

The catenary is a high availability system which has a lifetime up to 40 years. For the assessment of the service reliability the analysis of the incidents related to the studied system can be a good indicator of which component is critical in our system. The chart presented below shows the classification of the OCS incidents recorded from November 2014 to March for the French railway network.

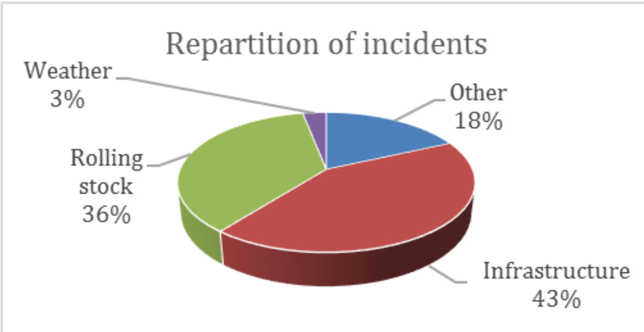

Figure 2. Repartition of catenary

In this chart the OCS incidents are classified regarding their causes, we distinguish four types of causes:

- Weather causes: lightning can cause insulators destroying, frosts or freezing rain can hinder the current collection on the contact wire, strong wind…
- Rolling stock equipment and traction: these are the failures of signaling, a lack of maintenance on a pantograph, or non-compliance with procedural rules.
- Infrastructure causes: this category regroups the electrical or mechanical failures of catenary materials
- Other causes: malicious acts, copper theft, falling objects, etc.

This chart highlights the causes of infrastructure failures which represent 43% of the incident impacting the service reliability. Subsequently, the infrastructure incident is studied to determine which component have more impact in terms of infrastructure failures.

This analysis showed that 50% of the infrastructure incidents were due to contact wire failures, 20% due to insulators failure, and 30% are due to other component failures or bad geometry of the catenary. Therefore, we can identify the contact wire and the insulators as the most impacting component for service reliability. The contact wire can be defined as a high criticality component (ISR = 3) and the insulators as a medium critical component (ISR = 2).

4.3. Identification of the OCS critical components regarding maintenance and downtime costs

In this section the critical components are selected regarding: overhaul, maintenance and downtime costs.

The maintenance of the OCS is organized regarding planned tasks consisting mainly of visual inspections and measurements, such as feeder temperature, contact wire height and stagger or inspection of tensioning device, etc. Automated measurement tools and new sensors can considerably reduce cost for this kind of inspections.

To determine the component which affect the most the maintenance a cost, regular meetings and workshops with variety of experts were achieved. It appears that the Contact Wire is the most critical and impacting component for the maintenance costs. Indeed, for example the maintenance budget for the OCS was about 186 millions of euros in 2007 for the French railway network. The renewal of the contact wire represents 48 millions of euros per year for replacement of 500km of contact wire. This represent about 25% of the OCS maintenance budget each year. Moreover, the local wear is 80% of factor of renewal of the contact wire.

Another aspect of this study was to identify the component the OCS which is the most impacting for downtime costs. The table below shows the contribution of the different OCS component on train delays:

Table 2. Contribution of components/sub-systems to OCS train delays.

Component/ Equipment	% contribution per delay category			IMC
	Short Delay	Long Delay	Cancelation or Delay >60min	
Support	0	0	0	0
Insulator	19.29	15.82	12.12	2
Steady arm	2.89	0.51	0	1
Contact wire	45.99	35.71	53.03	3
Feeder	5.4	3.57	7.58	1
Carrier	0	0	1.51	1
Suspension equipment	0	0	0	0
Power supply connections	2.25	10.2	1.51	1
Tensioning equipment	0	0	0	0
Section insulator	0	0.51	0	1

Train delays can be very costly for railway operators. The study of the distribution of train delays due to OCS components allows us to rank the most critical components regarding downtime cost. Regarding the contribution of components for train delays, and the previous considerations regarding maintenance costs, we can then define the IMC index for each component as described in the Table 2.

4.4. Critical component identification regarding system availability

In this step we select the component with the highest impact on downtime and failure rate. The aim is to identify the most critical failures affecting service and system availability. The approach proposed in this section is based on the four quadrant approach proposed in (Wang and Nee, 2009) for the identification of critical components.

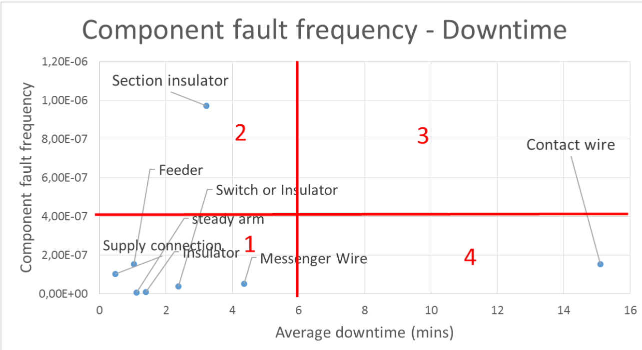

Figure 3. Four quadrant chart for OCS

The Figure 5 shows the component fault frequency for the OCS according to the average downtime of the system caused by components. Therefore, four quadrant numbered 1-4 are defined based on expert's knowledge and requirements. The quadrant 1 contains the components with a low average downtime and component failure rate, which it means that the actual maintenance policy work well for these components and the components have a low impact on service availability. Quadrant 2 contains the components with a high failure frequency and a low average downtime. An efficient diagnostic process can help maintainers to detect the failures of these components earlier and take actions more efficiently. The quadrant 3 comprise components with a high average downtime and a high failure frequency. This kind of components failures should be fixed at the design stage. The quadrant 4 include the most critical components as they have a low failure frequency with a high average downtime. A diagnostic and prognostic process can be applied to this kind of component to prevent their failure and estimate their RUL.

In the case of the OCS, the Figure 5 highlight the criticality of the contact wire which is a part of the quadrant 4, therefore we define an IA=3 index for this component. In addition, the quadrant 2 contains the insulator which allows us to define an IA=2 index.

4.5. Decision table for OCS

In this step, the criticality index CI of each component is calculated. The table 3 shows the obtained criticality for each component regarding the defined objectives.

Table 3. Decision table for OCS critical component ranking.

Components	Service Reliability (ISR)	Maintenance costs (IMC)	Availability (IA)	CI
Contact wire	3	3	3	9
Insulator	2	2	0	4
Section insulator	0	1	2	3
Steady arm	0	1	0	1
Feeder	0	1	0	1
Carrier	0	1	0	1
Power supply connections	0	1	0	1
Support	0	0	0	0
Suspension equipment	0	0	0	0
Tensioning equipment	0	0	0	0

The components are then ranked depending on their criticality. The contact wire has a high criticality in for the service reliability, maintenance costs and system availability. This analysis was confirmed by Alstom engineers and experts. A PHM program should give solution to monitor the contact wire and the other identified components such as insulators, section insulators, and steady arm, carrier, feeder and power supply connection. The study of the failure modes and the failure mechanisms will allow us to select the mature PHM solution for the OCS.

4.6. Define targets and parameters to monitor for the OCS

In this step, the failure modes and failure mechanisms of each component are studied. The aim is to identify and select the right parameters to monitor and select monitoring parameters. The figure 6 gives an example of the target definition for the contact wire:

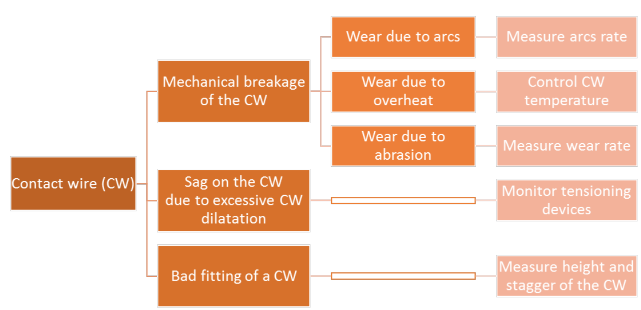

Figure 4 Procedure for monitoring parameters identification for the OCS

We define three failure modes for the contact wire (CW): mechanical breakage of the CW, sag on the contact wire due to excessive contact wire dilatation, and bad fitting of a CW. The sag of the CW due to its dilatation is caused by environmental conditions, for a PHM program a monitoring system of the CW dilatation can be a target to achieve. A bad fitting of the CW is consequence of a bad installation procedure, improper plans or mounting diagrams. It can also be caused by a failure of another component such as supports, steady arms or suspension equipment. In the context of PHM a continuous monitoring system for the height and the stagger of the catenary can be a solution to avoid this kind of failure. The last mode of failure which is mechanical breakage of the CW is often due to a local wear of the CW. Wear failure mechanism is due to three physical phenomena, mechanical wear, due to friction, electrical wear, due to current flow at the contact area between the CW and the pantograph stripes and electrical arcs. For wear mechanism we can define parameters to monitor as shown in the figure 6. Based the on these monitoring parameters a mature prognostics and diagnostics solution can be selected for the CW.

5. Conclusion

The main contribution of this article is the proposal of a methodology for components criticality determination regarding a PHM program deployment. The methodology is based on the analysis of the criticality of components through three objectives: increase service reliability, decrease cost impact of critical component, and increase system availability. The methodology was applied to the OCS system which is a large-scale distributed system and the procedure to select the monitoring parameters and define diagnostics and prognostics technology was presented. The procedure can be applied to other type of systems and his advantage is to give more impact benefits for a PHM system deployment as the critical components are identified through different topics. Moreover, the methodology can be extended by integrating a more efficient cost analysis based on the life cycle cost of the system regarding the critical components.

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