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What is This?

Data-driven model for maintenance decision support: A case study of railway signalling systems

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Abstract
Signalling systems ensure the safe operation of the railway network. Their reliability and maintainability directly affect the capacity and availability of the railway network, in terms of both infrastructure and trains, as a line cannot be fully operative until a failure has been repaired. The purpose of this paper is to propose a data-driven decision support model that integrates the various parameters of corrective maintenance data and to study maintenance performance by considering different reliability, availability, maintainability and safety parameters. This model is based on failure analysis of historical events in the form of corrective maintenance actions. It has been validated in a case study of railway signalling systems and the results are summarised. The model allows the creation of maintenance policies based on failure characteristics, as it integrates the information recorded in the various parameters of the corrective maintenance work orders. The model shows how the different failures affect the dependability of the system: the critical failures indicate the reliability of the system, the corrective actions give information about the maintainability of the components, and the relationship between the corrective maintenance times measures the efficiency of the corrective maintenance actions. All this information can be used to plan new strategies of preventive maintenance and failure diagnostics, reduce the corrective maintenance and improve the maintenance performance.

Introduction

The railway network is a complex system that requires several technologies to work together to handle the increasing demands on capacity, speed and mobility for the transportation of goods and passengers. Railway infrastructure managers need planning tools that enable them to systematically analyse and optimise budget needs and minimise the total costs while achieving the required levels of reliability, availability, maintainability and safety (RAMS), and guarantee the long-term quality of the railway assets.[1] In order to deal with the short-term cost and performance demands and to guarantee RAMS over time, systematic maintenance management of the railway assets is needed.[2] The EN 50126 standard[3] establishes the processes for the specification and demonstration of RAMS requirements in a railway network.

Railway signalling systems are composed of several different sub-systems, each with its own purpose; however, their interoperability is crucial to the signalling system as a whole. Previous studies have shown the importance of signalling systems for the dependable operation of the railway network.[4,5] Since signalling systems ensure the safe operation of the railway network, their reliability and maintainability directly affect the capacity and availability of the railway network, in terms of both infrastructure and trains. The functionality of the signalling system is based on the principle of fail-safe operation, meaning that the railway section where a failure is located will not return to full operation until the failure has been repaired (since safety cannot otherwise be ensured); hence, the dependability of the signalling system directly affects the capacity of the network.

Rail industry records show that for common railway signalling assets, the occurrence of no-fault-

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found (NFF) events can be as high as 50%.[5] The high number of NFF events can be attributed to a limited understanding of the root causes and characteristics of failures in complex systems, inappropriate means of diagnosing the condition of the systems, and the inability to duplicate field conditions.[6] Some research reported in the literature has shown the importance of NFF events, not just technically, but also organisationally and behaviourally, and has proposed addressing this issue as an integrated problem.[5,7–9] Granström[10] has described how the number of NFF events in railway signalling systems can be reduced by updating the maintenance requirements for these systems. Another important cause of failure is human error when performing corrective maintenance actions.[11,12] Other external factors, such as environmental conditions, can affect the number of corrective maintenance actions.[13,14] For a holistic picture of where failures are located and the dominant factors causing them, structured databases containing the complete information about the system are required.[15] A failure analysis based on empirical data recorded on the corrective maintenance work orders (WOs) would take the external factors into account and be able to measure their relative importance for the level of dependability of the system.

Maintenance managers responsible for deciding maintenance actions face large amounts of data and have a complicated task transforming these data into information that supports maintenance actions.[16] Failure analysis of a signalling system should give information about how this system is affecting the dependability of the operation and maintenance of the railway network, and identify possible areas of improvement. Pecht and Ramappan[17] found that the primary objective of failure analysis is to provide design feedback to improve the performance of a component. A number of proposals have been made to improve maintenance support performance by analysing maintenance data.[18,19]

Two approaches can be considered when studying the performance of a system. Although the intrinsic RAMS approach only depends on the design of the asset and the time required to perform a corrective action with no external factors involved, the operational RAMS takes into account the maintenance performance and the external factors particular to a location (the environment, human factors, random failures, logistics, etc.). Although, for the intrinsic approach, a model could be based on the theory of failure by studying the different components and the theory of failure for each of them, for the operational approach a data-driven model would be a better choice. This is due to the point that corrective maintenance records reflect the performance of the system with all the external factors involved in the operation and maintenance. Moreover, since signalling systems are a combination of mechanical, electronic and electrical components, the theory of failure becomes very

complex to model. A data-driven model can reflect the failure phenomena with greater accuracy than models based on the theory of failure.

The EN 50129 standard[20] lists methods to identify and evaluate the effects of faults on railway signalling systems, including failure mode, effects and criticality analysis (FMECA), fault tree analysis (FTA), and other methods based on historical data, i.e. common cause failure analysis and historical event analysis. We propose a decision support model for maintenance policies based on data-driven failure analysis of the corrective maintenance. A data-driven model considers all the factors when a system is in operation (e.g. the environment, human error, etc.) thus making it possible to quantify the probability that a failure will occur. It can be performed on a software-based platform using the WOs already recorded as input.

The purpose of this paper is to propose a data-driven decision support model that integrates the various parameters of corrective maintenance data, and to study the maintenance performance by considering different RAMS parameters. This model is based on failure analysis of historical events in the form of corrective maintenance actions. It is validated in a case study of railway signalling systems and the results are presented. The model allows the creation of maintenance policies based on failure characteristics, as it integrates all the information recorded in the various parameters of the corrective maintenance WOs. All this information can be used to plan new strategies of preventive maintenance, reduce the number of corrective maintenance actions, and improve the maintenance and operating performance.

Research methodology

Corrective maintenance records formed the basis of the analysis. A schematic diagram of the research methodology is shown in Figure 1. Internal documentation, a literature review and interviews with experts were keys to interpreting the data and discussing the results of the model. The research is based on data obtained from Trafikverket (the Swedish infrastructure manager). The corrective maintenance WOs for the railway infrastructure in Sweden are managed in Trafikverket's failure reporting system, called
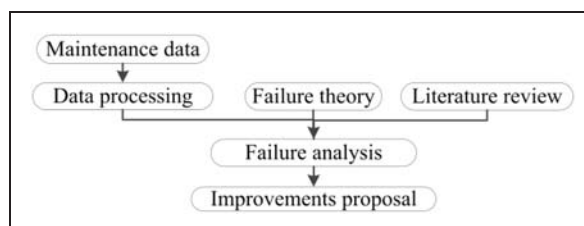

Figure 1. The utilised research methodology.

'Ophelia'. This system is based on the BMC Software Remedy, which was adapted to the specific requirements of the management of corrective maintenance for railway infrastructure. 0felia has its own manual for data analysis.[21]

The process of failure reporting is described in a document published by Trafikverket that specifies the appropriate procedure from the point in time when a failure is identified and reported to the system up to the point in time when the corrective action is finished and the WO related to the failure is closed.[22] A number of partners are involved in the process: the failure is generally identified by the train operator, the railway infrastructure manager controls the activity on the railway network, and a subcontracted company performs the corrective maintenance. Since some parameters in 0felia are registered manually and the data can be in several formats, processing the data is necessary to group the information into the correct parameters.

The IEC 61703 standard[23] relates the performance aspects of maintenance to the maintenance variables to measure the dependability of a system. In our case, based on the information recorded in 0felia, we consider the parameters that give the most information about failures. In order to identify these parameters, we performed an exploratory analysis that looked at the quality of the data recorded for each parameter (the amount of data recorded for each parameter and the quality of the information). This was needed because not all the parameters are indicated in a WO in 0felia.

Manuals, standards and interviews with experts helped us to define the parameters for our model.[21,22,24] Any parameter that had a low data quality (information not recorded or incomplete information) was discarded. The chosen parameters were analysed and the information was integrated to obtain the maximum possible information on corrective maintenance. We studied the values of the parameters themselves, their interrelations with other parameters and the variations over time.

Corrective maintenance WOs were gathered from Trafikverket's corrective maintenance database and then processed. The R software was used for the data processing and posterior analysis.[25] The failure modes, causes of failures and corrective actions were related to identify possible improvements, such as establishing an action procedure list for corrective maintenance performance. The times to restore were analysed to find patterns and to compare the total time to maintain (TTM) with the total time to restore (TTR).

A case study was used to validate the model; some of the results are summarised in this paper. Based on the analysis, we could identify the weakest points, such as a low reliability of components, problems with information accessibility, a high failure frequency, high TTR or/and TTM, problems identifying

failures, etc. The analysis allowed us to see where the general maintenance performance could be improved.

It is assumed that all the failures were recorded in the corrective maintenance database. One limitation of this research is that the failure data are related to a specific railway corridor, with specific environmental and operational characteristics. Since this research is based on empirical data, the results are limited to the information that could be obtained from the recorded data. Finally, the results showed here are limited to the system asset level for simplification.

Model description

To develop our model, we considered the different parameters recorded on the corrective maintenance WOs as the inputs for our model. Based on the results of the exploratory analysis of the corrective maintenance records, we included the following parameters in our model.

1. Symptom: a symptom that identifies a failure and triggers the opening of a WO, usually observed by the train driver and defined by reference to the affected system asset.
2. System asset/sub-system asset: the asset where corrective action is performed.
3. Failure mode: the real failure that is related to the corrective action.
4. Cause of failure: the reason for the failure.
5. Corrective action: the action performed in order to close the WO.
6. Failure date: the date the WO was generated.

Some conclusions can be made based on the times spent on the different WOs. From the database, we can extract the following times and dates for the corrective maintenance WOs: the times and dates for the failure identification, the opening of the WO, the start of the corrective action, the completion of the corrective action, and the closure of the WO. Our objective is not only to study the mean values for each parameter, but also to determine how the values are distributed. This will allow us to analyse how the maintenance performance is affected by external factors. We define three possible states for the assets during operation.

1. The available state, corresponding to the up-time (UT): the system is fully operative.
2. The unavailable state corresponding to the waiting time (WT): the time between the failure occurrence and the start of the corrective action. During the WT, the WO is opened, the failure is identified, the maintenance personnel are informed, the spare parts and tools are gathered, and the personnel go to the location of the failure.
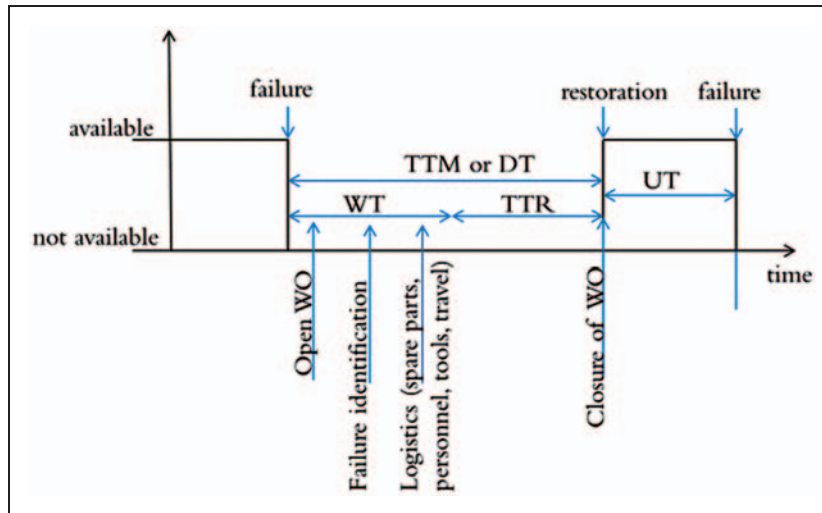
Figure 2. Correspondence between times.

3. The unavailable state corresponding to the restoration time (RT): corrective actions are performed and the WO is closed.

Based on these three states, we define the following parameters: the TTM, which is the total downtime (DT) when the system is not available for operation; the TTF, which is the time when the system is available for operation without a failure; and the relative restoration time (RRT), which is the ratio between the RT and the total DT (see equations (1), (2) and (3)). Figure 2 shows the correspondence between these parameters.

$$TTM = t(\text{finish of corrective action})$$
$$- t(\text{failure identification}) \quad (1)$$

$$TTR = t(\text{finish of corrective action})$$
$$- t(\text{start of corrective action}) \quad (2)$$

$$RRT(\%) = \frac{TTR(\text{sec})}{TTM(\text{sec})} \quad (3)$$

The number of failures in a determined interval is a measure of the reliability of the system, with the TTR and TTM indicating the maintenance support performance and the UT and DT showing the maintainability.[23] The cause of failure and the failure mode allow us to analyse the common cause failures, and with the failure data we can analyse the historical events. An analysis of the relationship between the various parameters on the corrective maintenance WOs yields insight into the RAMS parameters of the system and allows us to evaluate the maintenance performance of each asset.

Figure 3 shows the proposed decision support model based on the maintenance records. Different outputs are obtained. The most important are the measurement of failure rate, availability and maintainability performance not necessarily related to the system or sub-system asset. This provides a multidimensional tool for measuring the corrective maintenance and the associated parameters that do not depend on the affected asset. The link of the same corrective actions on different assets allows the comparison of procedures and identification of best practices.

The relation between causes of failure and failure modes allows the identification of the factors that most affect the reliability of the signalling system; further actions can be oriented to reduce those causes. The relationships between the different parameters, such as the relation between failure modes and corrective actions, and the RRT provide insight about the maintenance performance for the different failure modes and assets, which can give indications of the areas where an improvement would provide the most benefits in terms of maintenance optimisation. The relation between failure modes and failure causes can help to identify possible failure modes that could be suitable to consider for condition-based maintenance (CBM) in order to reduce the corrective maintenance actions.

Model implementation

The model can facilitate the continuous improvement of maintenance to meet dependability standards.[26] As Trafikverket considers standards of dependability[3] and RAMS[26] in its maintenance strategies, this model can be implemented as a part of its maintenance assessment process to measure maintenance performance, to analyse the results and determine further actions for dependability improvement (see Figure 4).

This model identifies possible areas for improvement in dependability, allowing companies to review their maintenance planning, preparation and execution. The model considers how various changes in maintenance policies (e.g. preventive inspections,
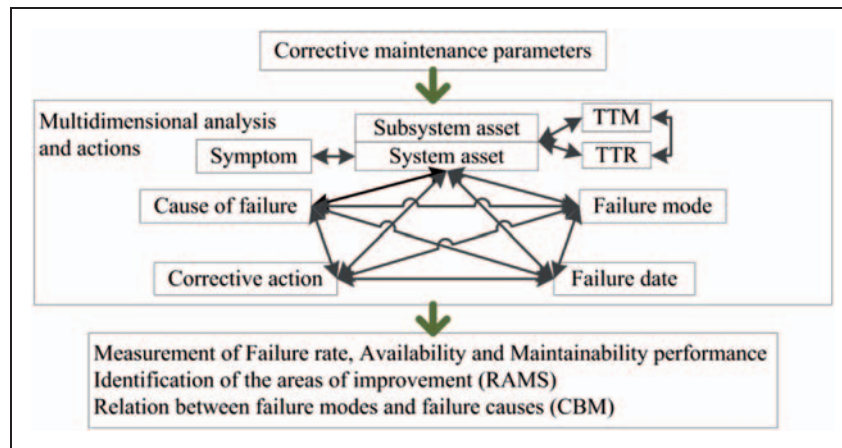
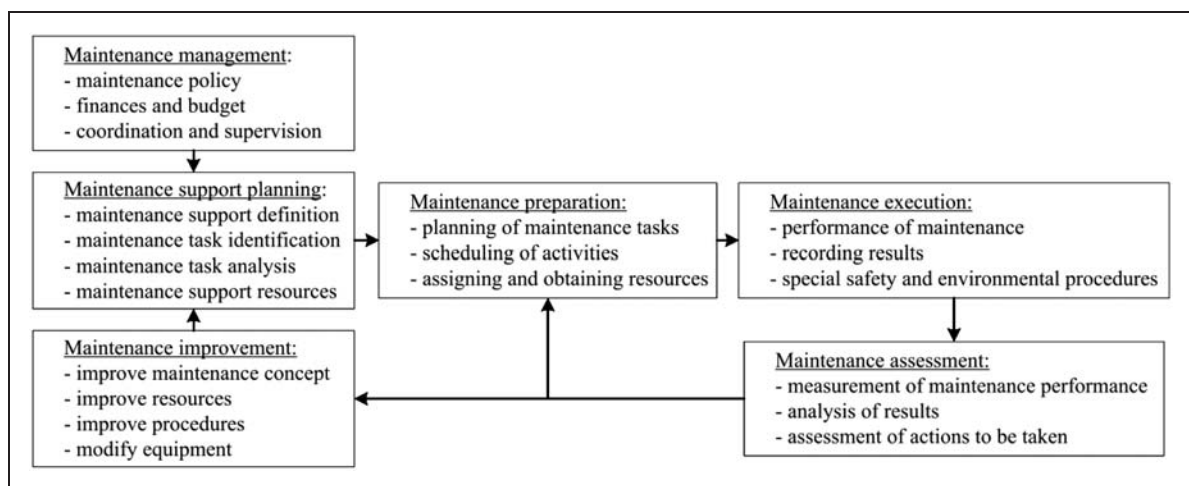**Figure 3.** Decision support model based on failure analysis.

Figure 4. Maintenance processes.[26]

corrective maintenance procedures, failure identification, etc.) affect the dependability of the systems (e.g. increasing availability and reliability, reduce TTR, etc.).

Finally, the model can also be an input when studying different maintenance policies and their life cycle cost (LCC) analyses. There are some uncertainties in LCC calculations due to the statistical characteristics of reliability and maintainability parameters, such as the MTTF and MTTR.[27] LCC analyses can be utilised to focus on maintenance strategies to minimise the maintenance cost in the system's life cycle, while meeting dependability requirements. Optimising the maintenance policy is a critical factor in achieving a cost-effective system in the long run. All such optimisations should aim at maximum system availability and minimum LCC and, in the case of Trafikverket, minimum train delays for a specific traffic scenario.[28]

Even though this paper focuses on signalling systems on the Swedish railway, the proposed model could be adapted to other railway systems or other networks. In the case of other systems on the Swedish railway, this would be directly applicable, since the information recorded in 0felia is the same for all assets that are part of the overall infrastructure. In the case of other railway networks or systems, the model remains valid, since the parameters considered constitute the basis for understanding and studying the dependability of any system; the only limitation would be the availability of the maintenance records required to implement the model.

Case study

The analysis is based on a fully operative railway line where the automatic train control signalling system supervises and controls the network. The line has been operative with no major changes for many years; hence, we can assume that the WOs represent maintenance and not design changes or failures. The data cover the WOs from January 2003 to November 2012 on a 203 km long line in the northern part of Sweden.

More specifically, 9030 WOs were registered during that period, of which 2455 were associated with signalling systems. Due to the number of WOs directly

related to signalling systems (27%) and in consideration of the critical nature of a good performance of the signalling systems, we focused our research on these systems, even though the methodology can be extrapolated to the whole railway network.

The signalling system in the corridor investigated in this case study is composed of the following systems.[24]

1. Track circuits, which are responsible for the train location.
2. Balise groups, which give input from the track to the on-board signalling system (e.g. speed limits, driving mode, etc.).
3. Level crossings, which coordinate the road traffic crossing the railroad.
4. Signals, which give permission to or place restrictions on the trains coming into a track section.
5. Signalling boards, which give fixed information to trains (e.g. tunnels, bridges, speed restriction areas, etc.).
6. Traffic management system (TMS), which is the interface between the traffic operator and the railway network.
7. Interlockings (IXLs) and radio block centre, which receive the input from the different systems (e.g. track circuits, level crossings, signals and the TMS), perform calculations and return as an output the train operation restrictions to ensure safe operation.

Every WO has associated values for the analysed parameters. The values found for each parameter include values for failure modes, causes of failure and corrective actions. More values can be considered, but since this research is based on empirical data, it focuses on the causes of failure for the signalling systems recorded in the corrective maintenance data.

The values found for the parameter of failure mode are as follows: 'not defined' (the failure mode is not specified in the WO), 'non-operative' (the asset is not working properly), 'NFF' (no failure was found), 'electrical', 'mechanical' and 'external'.

The following causes of failure for the signalling systems were recorded in the corrective maintenance data.

1. Design (e.g. improper design/installation/mounting, etc.).
2. Electrical causes, such as electrical overstress, improper isolation, abnormal feeding, power failure, etc.
3. Environmental causes, such as strong winds, extreme temperatures, thunderstorms, snow, ice, etc.
4. External reasons (e.g. railway vehicles, obstacles, third-party work, etc.).
5. Lack of maintenance or incorrect operation.

6. Mechanical reasons, such as fatigue, wear, mechanical overstress, etc.
7. NFF - no failure found (it was impossible to find any failure).
8. Not defined (unknown reason), which is recorded when the failure cannot be defined or is not described on the WO.

When the failure of a signalling system asset occurs, the different possible corrective actions performed to return it to the optimal state are classified into the following groups.

1. Repair or replacement (restoration) of the failed component.
2. Restart/software (SW) update when the failure is attributed to SW causes.
3. Provisional repair, but further corrective actions should be scheduled.
4. Adjustment/lubrication between modules/connections.
5. Cleaning or removal of obstacles (due to an external factor or dust accumulation).
6. Control of the system (it is not considered to need repair or replacement, or the failure could not be found, but certain symptoms indicate possible future failure).
7. Not defined (the action performed is not specified in the WO).
8. No action performed (it is considered that the system does not need the repair or replacement of a component, or the failure could not be found).

When studying the time to restore in the WOs, we found that, of the 2456 WOs related to failures of signalling systems, 103 WOs had a restoration time of 0 s. Only 19 of these had a corrective action that could be used to calculate the restoration time, such as 'repair' (one WO), 'replacement' (10 WOs), 'restart' (three WOs) and 'removal of obstacles' (three WOs). We decided not to consider these data, as their omission would not greatly affect the results of the analysis. The other abnormal result was that one WO had a negative time, probably due to an error when writing the 'correction action start date'.

Approximately 16% of the WOs have large times to restoration and maintain (more than a day). This can be due to different factors; e.g. the failure may not have affected the normal operation of the railway network and could wait for other scheduled maintenance activity; the complexity of the restoration may have been high; or it may have been difficult to identify where the failure was, etc. The procedures for corrective maintenance at Trafikverket state that a WO should be closed within a maximum of 24 h.[22] As a result we discarded any WOs that were open for longer than 24 h.
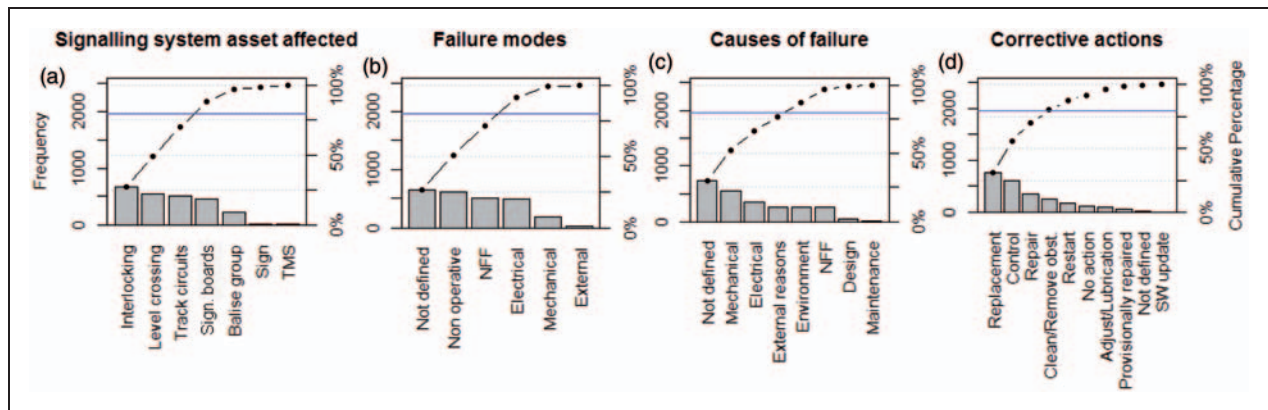
Figure 5. Pareto graphs showing the values for the different parameters: (a) signalling system asset affected; (b) failure modes; (c) failure causes; and (d) corrective actions performed.

A preliminary analysis could be made by determining the values for each of the parameters that were more important (considering the WOs that comprised 80% of the total). However, to state the maintenance characteristics and needs for each asset, we not only had to examine the total number of failures during the time frame of our sample, but also had to consider the yearly occurrences. This helped to show if the failures had occurred in one particular year (caused by specific environmental factors, for example), or if the results could be generalised. To study how the different parameters were related for the different assets in the railway signalling systems, we needed to find trends and differences in behaviour related to where the failure had occurred. The results of our analysis varied and are summarised in the next sections, together with a discussion of how to improve the dependability of the system based on our analysis.

Results

Figure 5 shows the Pareto diagrams for the chosen parameters (system asset, failure mode, cause of failure and corrective action); these parameters and the relationship between them will be summarised in this section.

The affected system asset

When examining the different system assets that comprise signalling systems, we found that the IXLs, the level crossings, the track circuits and the signals accounted for more than 80% of the failures overall (see Figure 5(a)).

When studying the failures by the year, we detected a maximum value of WOs related to signalling systems during 2010, followed by an improvement. The number of WOs for IXLs was significantly reduced (see Figure 6). At the same time, we observed an increase in the number of WOs for the track circuits, level crossings and balise groups during the last years. The results shown in Figure 5(a) and 6 led us to focus

our improvement measures on the RAMS of the following system assets: IXLs, level crossings and track circuits; this is because they produce around 80% of the WOs related to corrective maintenance. An improvement in the performance of these systems will improve the performance of the entire signalling system and, hence, the overall performance of the railway network.

The failure mode

The failure modes recorded are shown in Figure 5(b). The most common values recorded for this parameter are 'not defined' (26%), 'non-operative' (24%) and 'NFF' (21%). In other words, either there was no failure or it was not possible to identify a failure (hence, if there actually was a failure, it would remain unrepaired and the asset in question would fail again). Lacking the proper data can cause an increased amount of time to be devoted to corrective maintenance actions, as incorrect failure identification decreases the system availability.

Table 1 shows the relationships between the system's asset parameters that are affected and the failure modes. Based on these data, we can identify how the system assets fail. The most common value recorded for the failure mode of the IXLs is 'non-operative'. We can assume that one of the reasons for these results is the complexity of the system where the failure occurs in the case of the signals and the level crossings. For the balise groups and track circuits, 'NFF' is the most recorded value for the failure mode.

The cause of failure

The types of causes of failures related to the signalling systems are shown in Figure 5(c). The most recorded values for this parameter are 'not defined' (29% of the WOs), 'mechanical' (23%) and 'electrical' (14%). Other values recorded for the cause of a failure, such as 'external', 'environment' and 'NFF', are also
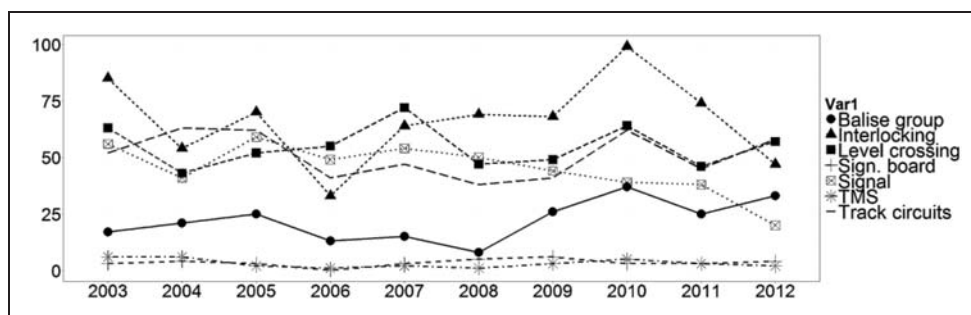
Figure 6. Failures of the signalling systems based on the year and system asset.

Table 1. Failure modes of an affected system asset.

Failure mode	Affected system asset						
	Balise groups	IXLs	Level crossings	Sign. boards	Signals	TMS	Track circuits
Electrical	15	71	54	0	207	5	140
External	1	4	9	1	4	0	1
Mechanical	16	31	92	10	26	0	10
NFF	80	86	107	2	66	6	162
Non-operative	55	290	84	2	51	4	118
Not defined	53	181	202	19	96	16	78

Table 2. Cause of the failure of an affected system asset.

Cause of failure	Affected system asset						
	Balise groups	IXLs	Level crossings	Sign. boards	Signals	TMS	Track circuits
Design	8	16	7	0	6	4	5
Electrical	14	166	43	14	53	6	47
Environment	5	82	129	2	10	1	24
External	16	22	99	0	17	0	105
Maintenance	1	6	11	1	4	0	0
Mechanical	29	143	96	7	210	6	59
NFF	40	35	47	0	37	3	87
Not defined	107	193	116	10	113	11	182

relevant, each represents 10% of the WOs recorded. Clearly, the causes of failures of the signalling systems are quite widely distributed, and the data should be studied in more depth to find possible trends.

Different assets have different failure causes, since their architecture and operating conditions differ. Studying the causes in terms of the asset where the failure occurred, we can identify some trends. The different causes of failures recorded for the various system assets are listed in Table 2.

The most commonly recorded value for the cause of failure for four of the seven systems is 'not defined'. Signalling boards have an 'electrical' cause and signals have a 'mechanical' cause as the most common failure cause. Electrical causes derive from thunderstorms

affecting the cable that connects the signalling board to the ground. For the signals, the mechanical causes of failure are higher because failures in assets such as the signal lamp or bulb are recorded as being mechanical in nature.

The corrective actions

The corrective action parameter consists of the actions that were performed to restart the system after it failed. The most common actions recorded for the signalling systems (see Figure 5(d)) are 'replacement' (31%), 'control' (24%), 'repair' (14%) and 'cleaning or removal of obstacles' (11%). The architecture of most signalling systems is modular,

Table 3. Corrective action for an affected system asset.

Corrective action	Affected system asset						
	Balise groups	IXLs	Level crossings	Sign. boards	Signals	TMS	Track circuits
Adjustment/lubrication	10	23	32	6	27	1	5
Cleaning /removal of obstacles	5	20	139	1	19	0	76
Control	99	119	128	2	90	6	158
No action	7	15	5	0	17	0	71
Not defined	2	8	5	1	7	0	5
Provisional repair	0	26	9	2	3	4	19
Repair	23	82	71	15	49	2	101
Replacement	65	268	131	3	227	9	64
Restart	9	101	28	4	11	9	10
SW update	0	1	0	0	0	0	0

Table 4. Corrective action based on the failure mode.

Corrective action	Failure mode					
	Electrical	External	Mechanical	NFF	Non-operative	Not defined
Adjustment/lubrication	21	0	11	2	12	58
Cleaning /removal of obstacles	90	1	6	16	20	127
Control	16	7	1	402	7	169
No action	7	0	0	80	1	27
Not defined	5	1	3	5	2	12
Provisional repair	13	0	9	0	27	14
Repair	54	4	48	1	171	65
Replacement	267	2	91	1	325	81
Restart	19	5	16	2	39	91
SW update	0	0	0	0	0	1

allowing the replacement of an asset that fails with a new one, reducing the time for restoration of operation.

Table 3 shows the relationship between the system assets and the corrective actions. For the track circuits and balise groups the most common action is a control action (45% and 31%, respectively), whereas for the IXLs and signals, for example, replacing a failed component is more important (40% and 50%, respectively). For the TMS, the most common corrective actions are replacement and restart, both corresponding to 29% of the WOs. Balise groups and track circuits are easily affected by environmental or external factors (they are located along the track), and their failure may not be permanent. IXLs are designed as lineside replacement units (LRUs) to optimise maintenance while promoting replacement over repair on-site so as to minimise the DT of the system. Balise groups have replacement as the second most common corrective action. Since the failure of a balise can affect the operation of the track section where it is located, it is more effective to replace the balise with a new one, rather than taking the failed one to the workshop to study the failure, thus minimising the DT.

Relationship between 'corrective action' and 'failure mode'

Table 4 shows the relationship between the parameters 'corrective action' and 'failure mode'. The number of 'NFFs' linked to the corrective action 'control' contributes to making this measure one of the most commonly recorded corrective actions for the signalling systems. The most common corrective actions are a 'control' and 'replacement' of the asset. For example, 'control' is related to the following values for 'failure mode': 'external', 'NFF' and 'not defined'; whereas 'replacement' is associated with the following values for 'failure mode': 'electrical', 'mechanical' and 'non-operative'. This is due to the modular architecture of signalling systems and the high incidence of 'NFFs' and 'not defined' failure modes.

Table 5. Relationship between failure mode and cause of failure.

Cause of failure	Failure mode					
	Electrical	External	Mechanical	NFF	Non-operative	Not defined
Design	5	2	3	2	11	23
Electrical	62	1	15	3	172	90
Environment	32	0	7	15	65	134
External	73	5	66	7	62	46
Maintenance	2	9	1	3	0	8
Mechanical	234	0	67	0	193	56
NFF	5	0	0	211	1	32
Not defined	79	3	26	268	100	256

Table 6. TTM, TTR and RRT.

	Minimum	1st Quartile	Median	Mean	3rd Quartile	Maximum
Maintenance time (TTM, (s))	180	4560	8700	16,580	17,400	86,340
Restoration time (TTR, (s))	60	1260	3060	6094	6960	83,880
Relative restoration time (RRT, (%))	0	19	43	45	70	100

In fact, 10% of the WOs are related to the corrective action of 'cleaning / removal of obstacles'; of these, most are either 'not defined' or 'electrical' failure modes. This could be due to the effect of rain and snow on operation. A total of 53% of the WOs related to the corrective action 'restart' have a failure mode of 'not defined'. This could be associated with the difficulty of identifying the failure mode of electronic assets. There are fewer appearances of the corrective action 'provisional repair' associated with the failure modes 'non-operative', 'not defined' and 'electrical'. This low rate reflects the modular nature of signalling systems, for which the most common repair action is the replacement of the LRU.

Relationship between 'failure mode' and 'cause of failure'

When analysing the failure data, it is important to remember that different values can refer to the same kind of failure, since there is no exact way to evaluate them. This can be seen when comparing the parameters 'failure mode' and 'cause of failure' (Table 5). For example, 37% of the WOs where the cause of failure was recorded as 'not defined' have 'NFF' as the failure mode. With regard to the WOs where the failure mode was recorded as 'non-operative', 32% of the failures were mechanical failures, 29% electrical failures and 16% were not defined.

In fact, 78% of the WOs relate to environmental issues and 42% of the WOs relate to external reasons to have a failure mode of 'not defined' or 'non-operative', possibly because it was not considered relevant to describe how the cause affected the asset when recording the WO; it was considered enough to simply state that the system asset was not working properly.

Relationship between the system asset affected, restoration time and maintenance time

Table 6 shows the main parameters for the TTM, TTR and RRT for the whole signalling system; note that approximately half of the total time is due to the restoration time (46%). A number of factors can influence these values, including failure mode identification and specification of the repair requirements, the distance to the failure location, human and/or material resources, etc. We can compare the maintainability between the different system assets by comparing the respective values of the mean time to restoration (MTTR), mean time to maintain (MTTM), mean waiting time (MWT) and mean relative time to restore (MRTTR) obtained from the empirical data.

Figure 7 shows the relationship between the time variables (MTTM, MTTR and MWT) for the different system assets. As can be observed, the values for the MTTM and MWT have the same relationship in all the systems with the exception of the TMS, where the MTTR is proportionally much higher. The other major result is the lower value of the MWT for the level crossings and the TMS. This is due to the critical nature of these assets, as well as the ease of access of the asset locations.

Figure 8 visually summarises the RRT for system assets affected by a failure. This figure shows the
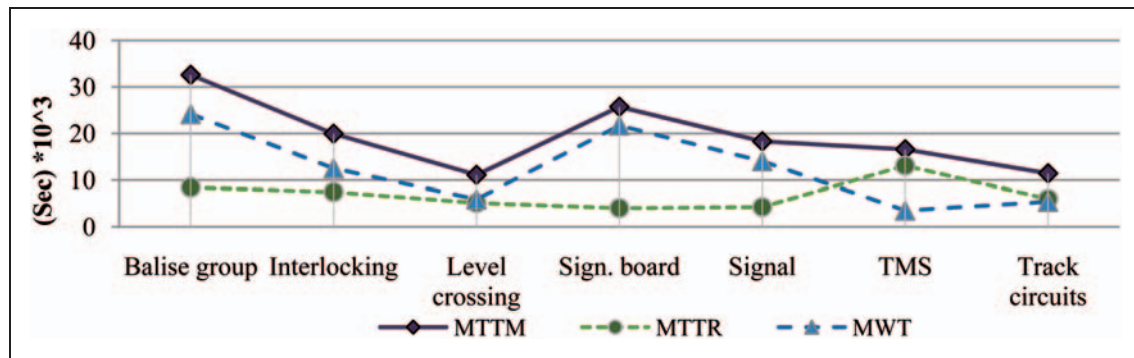
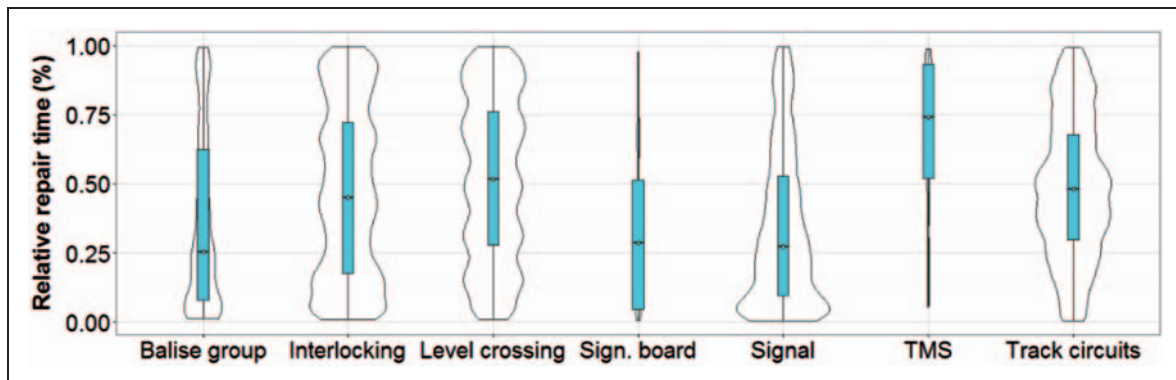**Figure 7.** MTTM, MTTR and MRTTR for the system assets.

Figure 8. Relative restoration time for the system assets.

maximum and minimum times spent on restoration, along with the median and first and third quartiles. The density distribution is shown by the perimeter of the boxplots, and the thickness depends on the number of WOs associated with a failure of the system asset. It can be observed that the different relationships between the TTR and TTM depend on the asset affected.

For example, the mean values for the level crossings, signals and signalling boards are quite similar and slightly lower than those for the other assets. It is possible that failures of these systems are easier to identify, since their architecture is simpler than that of systems such as IXSs or the TMS. Systems with a more mature design (i.e. a design that has not been modified to a great extent) are more familiar to the maintenance personnel than other systems; hence, the personnel's knowledge of the failure modes and their corresponding corrective actions is greater. For other systems, such as the TMS, the time to restore is higher, mainly due to the complexity of the architecture, which hinders failure identification and restoration. Some systems show an increase in the number of WOs for low restore times (e.g. the level crossings, signals and track circuits). One possible cause is the ease of identification of failures and the quickness of restorations of these systems (e.g. replacing the lamp of a signal); another possible

cause is the impossibility of finding failures (NFF) on occasions.

For the system assets mostly affected by mechanical failures (e.g. signals and signalling boards), the relative restoration time is proportionally smaller and the distribution of the relative restoration time decreases when the values of TTR and TTM are more similar. Mechanical failures may be easier to identify; assets prone to mechanical failure also have a simpler architecture that facilitates repair or replacement, reducing the TTR. The balise groups also have a smaller relative restoration time, even though most of the failures are electronically based, due to the simplicity of their architecture.

For the electronically based system assets with a more complex architecture (e.g. IXLs and the TMS), the relative restoration time is proportionally higher than that for the mechanically based assets, and the distribution of the relative restoration time does not show a trend. Arguably, more time is spent on identifying the failure that has occurred and finding the proper corrective action.

NFFs are more common for electronically based systems and the architecture of these systems is more complex. Better knowledge of the systems to be maintained can reduce the time needed to identify the required corrective maintenance action in these cases.
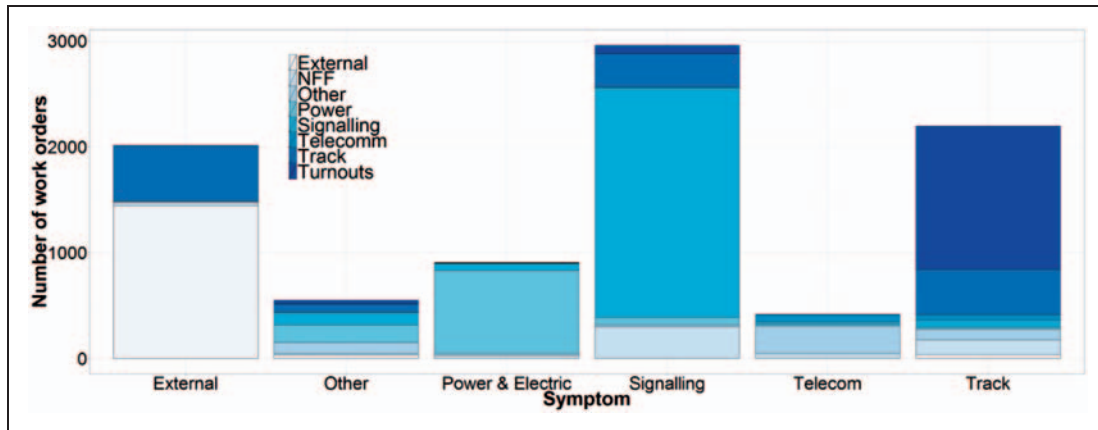
Figure 9. The system where the failure actually occurred related to the symptom.

Relationship between the symptom and system asset affected

We studied the relationship between the parameters 'symptom' and 'system asset affected' to determine how much information could be extracted from the former. When a WO is opened, there is a symptom indicating where the failure has occurred. Failures are usually identified by the train driver, and it is not always possible for them to make an accurate identification of the failure, since failures of different systems may have the same failure effect (e.g. it can be difficult for a train driver to differentiate between a failure in the track circuit and a signal failure). The values of the 'symptom' parameter are associated with the different systems; therefore, they may differ from what was reported when the WO was opened and from the system where the failure actually occurred.

To maximise the usability of the symptom parameter for giving information on the real failure, we grouped the systems into more generic groups, such as signalling systems (including track circuits, signals, IXLs, etc.), power and electric systems (e.g. transformers, substations, etc.), telecommunication systems (e.g. radio, telephony, signal cable, etc.) and track systems (turnouts, rail, etc.). When the system was not defined, it was classified as 'other systems' and, when no fault was found, it was classified as a system with a NFF. Figure 9 shows the relationship between the symptoms and the system groups affected; the identification given by the symptom mostly relates to the affected system asset.

Having a more general classification of the symptoms may result in better accuracy; in addition, data classified in this manner can be used by the maintenance personnel. Therefore, using broader groups for the symptom classification can give the maintenance personnel a better initial idea of which technology has failed.

Discussion

Based on the number of WOs related to failures, we conclude that signalling systems play an important role in the dependability of the railway system. IXLs, level crossings and track circuits are the systems most affected by failures and cause most of the WO actions. Improving the performance of these systems will improve the overall performance of the railway network.

'Non-operative', 'not defined' and 'NFF' are the most common values recorded for the failure mode for signalling systems. There are two possible reasons for this: either there was no failure or it was not possible to identify a failure (hence, if there actually was a failure, it would remain unrepaired and the asset in question would fail again). The most common value recorded for the cause of failure is 'not defined'. A comparison of the number of WOs for each system and the real failure recorded shows that the more complex the system is, the more often a clear failure mode is not identified. Identifying failures in electronically based systems presents some difficulty, since ageing in such systems is not directly visible (unlike mechanical fatigue). This can be seen in the high number of WOs with the following values recorded for the failure mode: 'NFF', 'not defined' or 'non-operative'; these WOs concern failures for which the failure mode was not identified, and either no action was taken or the component was replaced. These WOs require extra time for corrective maintenance due to the time spent trying to identify a failure (sometimes unsuccessfully).

The complexity of the system and the maturity of the design architecture (e.g. it is easier to identify failures in a well-known system) play an important role when identifying failure and performing corrective maintenance actions. Better knowledge of the systems to be maintained can reduce the time needed to identify the required corrective maintenance action.

Factors such as environmental conditions or electromagnetic compatibility can affect the normal operation of the assets, producing random failures, for which it is difficult to identify the failure cause and mode. Better failure identification would lead to better preventive measures, reducing the occurrence of failures or minimising their effects.

Studying the relationship between the corrective actions and the systems affected allows us to examine the maintainability of the various systems, and to propose improvements to reduce the time for corrective maintenance actions and increase the efficiency and efficacy of such actions. A review of the corrective maintenance procedures can help to achieve this goal.

The study of failure modes and their occurrence allows a better understanding of the reliability of the system, allowing the possibility of developing hybrid reliability models combining physics of failure and data-driven models to study failure prognosis and remaining useful life. This model, together with other methodologies such as FMECA and FTA, allows companies to review their preventive maintenance inspections, with special emphasis on the most frequent failure modes. Finding the link between failure modes and failure causes assists in reviews of preventive maintenance and CBM, yielding insight into how operational and external factors affect the reliability of the system and suggesting ways to either minimise their effect or monitor them to adjust the estimated remaining useful life. Studying the causes of failure can facilitate a better understanding of the failure modes, even on WOs where little information is recorded (e.g. in the case of 'not defined' and 'non-operative'). Linking the failure modes to the failure causes and corrective actions performed can help to reduce the time for failure identification, which leads to a reduction in the time needed to perform the corrective maintenance action (leading to improved availability).

From our observations of the TTM, the TTR and the relative RT, we conclude that, depending on the system asset, a number of different factors can influence the times required to maintain and to restore. Analysing the values for the factors affecting maintenance performance for each system can help reduce the time spent on corrective maintenance, thus improving the dependability of the system. Proposals for improvement depend on the focus; e.g. one can reduce the waiting time by improving the maintenance support, and one can decrease the RT by striving for a more efficient corrective maintenance performance, etc.

Depending on the system asset, different factors can influence the TTM and TTR for different reasons; examples of such factors are failure mode identification, specification of the repair requirements, the distance to the failure location, human and/or material resources, etc. Analysing the values of the factors that affect the maintenance performance for each system can help to reduce the time spent on corrective maintenance and improve the dependability of the system.

Conclusions

The purpose of this paper was to propose a data-driven decision support model that would integrate the various parameters of corrective maintenance data and study maintenance performance by considering different RAMS parameters. To develop our model we considered the different parameters recorded on the corrective maintenance WOs as the inputs for our model. The output of the model is the relations between the different parameters and a presentation of the relations that occur more frequently. This makes it possible to review the current maintenance policies and propose continuous improvements depending on the current performance. A limitation of the model is its dependence on the quality of the data recorded on the WOs. Depending on the quality of the input data, the reliability of the output for the decision support process can vary.

The proposed model is based on failure analysis of historical events in the form of corrective maintenance actions. It has been validated with corrective maintenance data from a specific case study. We have focused on signalling systems for two reasons. First, the failure of a signalling asset may mean that the railway section where it is located will be not fully operative until the failure has been repaired (since safety cannot otherwise be ensured); hence, the availability of the whole railway section will be affected. Second, signalling systems receive a great deal of corrective maintenance WOs (27% in our case study).

Implementation of the proposed decision support model has shown that it can be successfully applied, with the following results.

1. The model treats the failure occurrence from a holistic perspective; it integrates the information recorded in the different parameters of the corrective maintenance WOs.
2. The model is based on empirical data and can therefore be used to validate results from other methodologies.
3. The model allows companies to review how changes in maintenance policies (e.g. scheduled maintenance and inspection procedures) affect corrective maintenance performance.
4. New policies can be oriented to a reduction of the most common causes of failure and to an optimisation of the most frequent corrective actions to reduce the time spent on maintenance.
5. The need to improve failure identification and reduce the number of WOs with 'not defined', 'non-operative' and 'NFF' recorded for the failure mode is indicated by the number of WOs with these values recorded. Improvements in

knowledge transfer and information logistics could reduce their number.

6. The model links failure modes and causes of failure, establishing the basis for possible future improvements, such as the implementation of CBM (e.g. CBM of track circuits depending on the rainfall).

7. The model identifies the assets that affect railway availability most; improving their reliability will maximise the global benefits.

Signalling systems are designed based on the 'fail safe' mode; a failure can mean that the railway section where they are located will be not fully operative until the failure has been repaired. Hence, the failure of a single component can affect the availability of the whole railway network. The model identifies the systems that are more likely to fail, the causes of failure and the most common corrective actions. Maintenance policies can be proposed to improve the reliability and availability of these systems.

From the results of the case study, we conclude that signalling systems play an important role in the dependability of the railway system, and this is particularly true of such assets as IXLs track circuits and level crossings. We also find that 'non-operative', 'not defined' and 'NFF' are the most common values recorded for the failure mode. Further research on the NFF phenomena can help to optimise maintenance performance and reduce the corrective maintenance WOs.

For the analysis performed in the presented research study, we assumed that all the failures were recorded in the corrective maintenance database. Since this research is based on empirical data, the results are limited to the information that could be obtained from the recorded data. Further research can reduce these limitations and examine the results more closely.

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