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INNOTRACK

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D3.3.6 – Quantification of benefit available from switch and crossing monitoring

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1 Executive summary

This document details work undertaken in the Switch and Crossings sub-project of the Innotrack project. Specifically, the document details work that was undertaken by the University of Birmingham, Vossloh and Banverket to determine the benefits of switch and crossing monitoring.

This document builds on previous work undertaken in the Innotrack project that has focussed on specifications for practical switch and crossing monitoring and the development of algorithms for the detection and diagnosis of incipient faults. To date, work in the Innotrack project has considered the application of monitoring to both AC and DC electro-mechanical switch mechanism.

In assessing the costs and benefits of installing automatic condition monitoring equipment, it is useful to define several levels of capability. It may be uneconomical to install the same level of capability across the entire network, because lightly used routes may not need the same level of intensive maintenance attention as heavily used routes. The analysis described in this report begins by considering five levels of monitoring system capability that may be appropriate for practical installation.

Two approaches for calculating the financial benefits of condition monitoring are presented. The first is a straightforward estimation of the changes in life-cycle costs over an entire switch system (as considered by Banverket). The second is a capability-based study of the costs and benefits of introducing different capability levels onto an existing asset; the costs modelled in this study are mostly savings due to reductions in delays (as considered by Network Rail).

Here, the two models are used together in order to determine the course of action required for a particular asset case, based on the known failure statistics.

2 Glossary of terms

CBM	Condition-Based Maintenance
MTBF	Mean Time Between Failures
MTBM	Mean Time Between Maintenance
MTTR	Mean Time To Repair
MWT	Mean Waiting Time
NPV	Net Present Value
PV	Present Value
RCM	Remote Condition Monitoring

3 Qualitative benefits of condition monitoring

3.1 Monitoring and maintenance capabilities

In assessing the costs and benefits of installing automatic condition monitoring equipment, it is useful to define several levels of capability. It may be uneconomical to install the same level of capability across the entire network, because lightly used routes may not need the same level of intensive maintenance attention as heavily used routes.

Five levels of capability are defined here. It is fair to assume that with each progressive level, the complexity of the system increases. However, with a systems engineering approach to the system's design, most of the expense is likely to occur in the installation of level 1 capability. Further improvements should be possible with minimal hardware changes across the network. This is because the difference in the amount of distributed hardware required between levels 1 and 4 is negligible, providing adequate measuring capability is installed at the outset. The only changes are made in software and the user interface which provides system outputs to the maintenance staff.

3.1.1 Level 0 capability: detection of failures

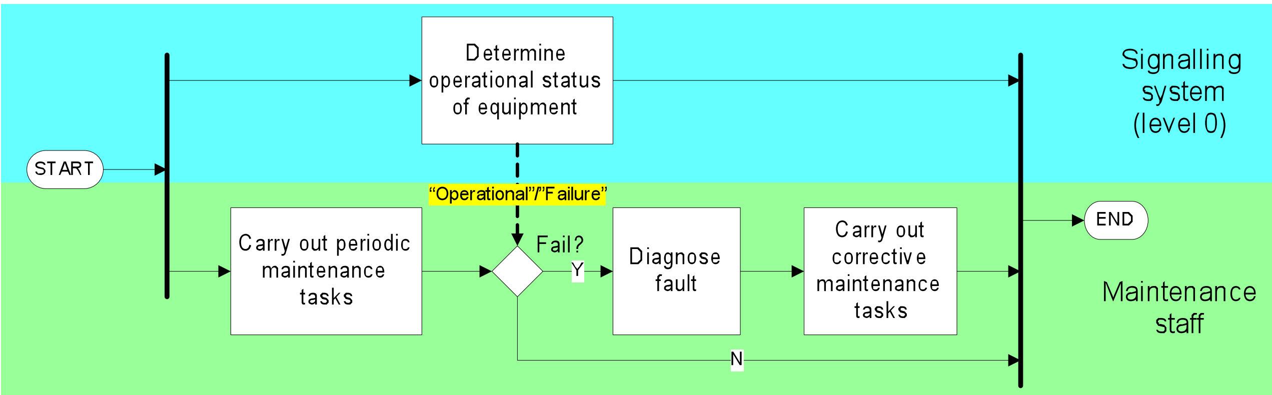

Figure 1 - Flow diagram illustrating the level 0 monitoring capability

Figure 1 illustrates the operations carried out in a maintenance system which has level 0 capability. In this traditional periodic maintenance regime, the risk of failure is mitigated by performing maintenance at conservatively-calculated intervals. These maintenance tasks include inspections and measurements as well as interventions. If an asset fails, the signalling system detects it because safety considerations in signalling design mean that assets must be verified to be operational for trains to be signalled onto the route.

Should an asset fail, the maintenance staff are required to attend on site as soon as possible, examine the asset, diagnose the fault using their human senses and experience, and carry out corrective maintenance as they deem appropriate.

Most modern railways have level 0 capability installed as part of the signalling system. For switches and crossings this takes the form of the detection lines which verify that a switch is in the correct end position; should the end position signal be absent then it is fair to conclude that the switch has failed to operate correctly.

Level 0 capability has serious limitations: first, the periodic maintenance tasks are carried out at intervals designed to mitigate risk with a considerable safety margin; therefore more cost is incurred than is strictly necessary to ensure continuing operation. Second, these tasks involve sending staff to the asset site on a regular basis, exposing them to the usual safety risks of a running railway. This could be avoided. Third, because there is no monitoring of the key parameters within an asset, the maintenance staff only have their own senses available to assist them in determining the true condition of the asset; this limits the insight they have into the machine's operation. Fourth, since corrective maintenance is only carried out once the asset has failed, this causes severe disruption to train services if the failure occurs at a busy time.

3.2 Level 1 capability: detection of faults

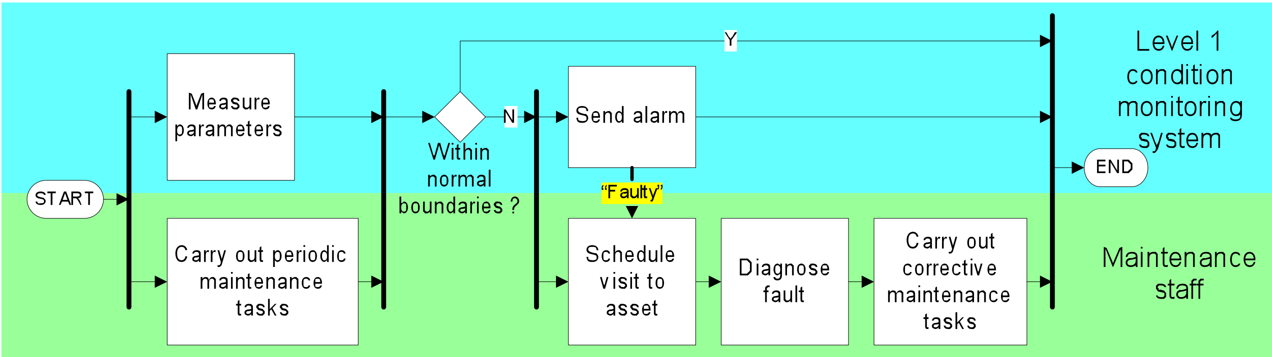

Figure 2 - Flow diagram illustrating level 1 condition monitoring capability

Figure 2 shows the processes carried out in a maintenance system with level 1 capability. The condition monitoring system measures key parameters on the asset and determines if the measurements are indicative of a healthy asset or a faulty one. If a fault is suspected, an alarm is sent to maintenance staff, who must then examine the asset and fix whatever fault is present.

This capability is useful in that it can detect faulty behaviour before an asset failure occurs, giving the possibility of correcting the fault at a time of the maintainer's choice, avoiding disruption to traffic. However, most of the intelligent tasks are still left to the maintenance staff, who still rely only on their senses and experience to correctly diagnose and fix the fault.

3.2.1 Level 2 capability: diagnosis of faults

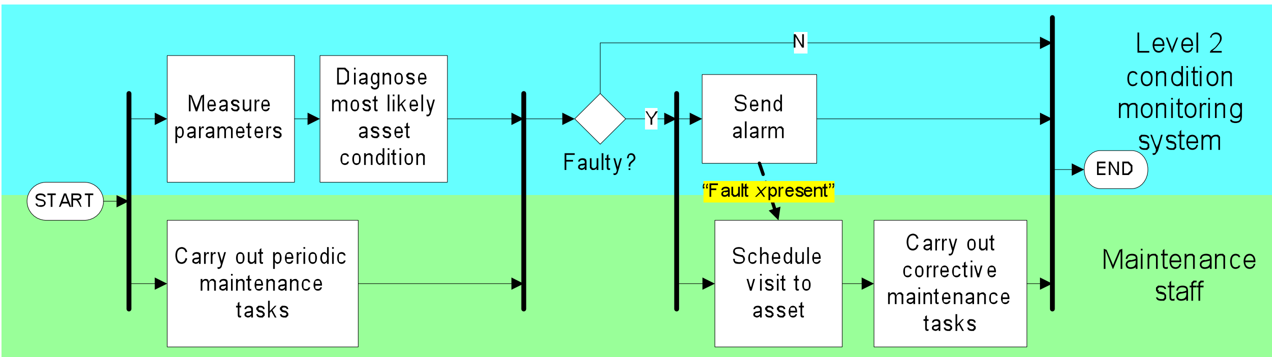

Figure 3 - Flow diagram illustrating level 2 condition monitoring capability

Figure 3 shows how a maintenance system works when level 2 capability is introduced. Now, the automatic system determines the condition of the asset; when a fault develops, the alarm now gives the maintenance staff an idea of what fault is present, allowing them to better schedule visiting time and choose the correct mix of tools and skills to tackle the fault. However, there is no indication as to how severe the fault is, making scheduling difficult: ideally, maintenance should be carried out during quiet times on the railway, but with no indication of how much time remains before the asset fails, the maintainers must weigh the risks of the asset failing when deciding when to make their visit.

3.2.2 Level 3 capability: time-to-failure calculation

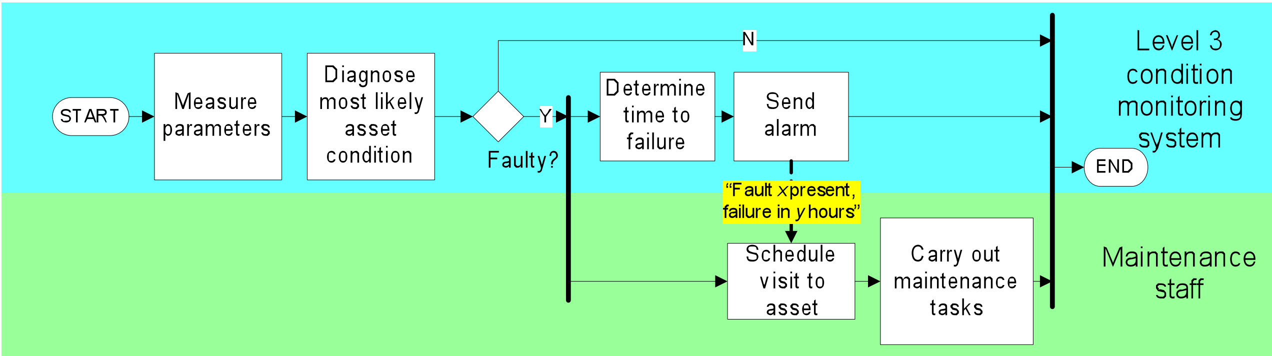

Figure 4 - Flow diagram illustrating level 3 condition monitoring capability

Figure 4 shows the workings of a maintenance system with level 3 monitoring capability. As with level 2, the monitoring system provides advice on the nature of faults to the maintainer. Now, however, the maintainer is also given an indication of how much time remains before a failure occurs. This gives the possibility, *providing that the monitoring system can pick up all faults*, of dispensing with periodic maintenance and making all maintenance decisions based on the time-to-failure calculation provided by the automatic monitoring system. The maintenance staff are, however, still required to make decisions on task scheduling and the prioritisation of work between different actuators.

3.2.3 Level 4 capability: automatic scheduling of condition-based maintenance

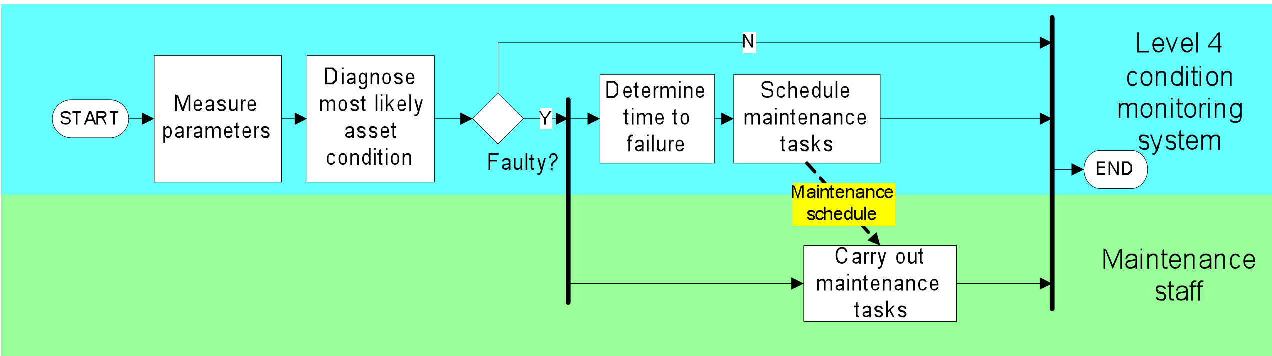

Figure 5 - Flow diagram illustrating level 4 condition monitoring capability

Figure 5 shows a maintenance regime where the monitoring system has level 4 capability. In this regime, condition-based maintenance is carried out, with all decisions being made by the automated system, which simply gives a schedule of maintenance tasks to the staff.

In order to do this, it must prioritise the severity of all possible fault conditions, and schedule tasks to address those failure modes which are most urgent.

3.3 Comments on the qualitative benefits of higher condition monitoring capability

3.3.1 Mechanisms for reducing life-cycle costs through condition monitoring

Improved condition monitoring capabilities can reduce the life-cycle costs of S&C in several different ways. To begin with, it is important to define which costs are to be attributed to the S&C. The list below points out some obvious and some subtle areas of cost where improved condition monitoring may have a positive impact.

1. Parts and labour costs for maintenance & inspection tasks carried out on S&C
2. Cost of delays caused by S&C failures
3. Cost of delays caused by S&C maintenance at inconvenient times
4. Costs arising from the increased risk to staff maintaining/inspecting S&C on running railways
5. Installation cost of S&C where it is linked to the length of the life-cycle

Item 1 is the largest direct cost during the life cycle of a switch, accounting for as much as 50% of the total LCC[1]. Improving condition monitoring capabilities can progressively reduce these costs as the capability increases.

In cases where delays are attributable to the infrastructure manager, item 2 becomes relevant. The costs of delays caused by S&C failures can be directly allocated as a life-cycle cost for each asset. By adding monitoring capabilities, it is possible to reduce the failure rate progressively and thus reduce the cost of resulting delays.

Item 3 refers to the amount of periodic maintenance carried out in maintenance systems of capability level 2 or lower. This maintenance has to be carried out at some point, and goes against the modern aspiration to have a railway which runs 24 hours a day, 7 days a week. By reducing or eliminating periodic inspections, the cost of S&C unavailability can be reduced. With better monitoring, maintenance can be targeted more effectively and become more efficient, saving further costs.

Item 4 is directly linked to the amount of time maintenance staff spend on or near the track during traffic hours. By reducing this, staff are exposed to less risk (because the probability of an accident is reduced). Although modern safe systems of work are a vast improvement on traditional working practices, they also cost a lot more because more staff are required and they need to be highly trained. The consequences of accidents involving track workers are more severe in modern times, where an infrastructure manager is subject to public scrutiny and legal action.

Item 5 is a whole-life opportunity for the improvement of the general condition of an asset. If improved monitoring capabilities mean that assets are generally kept in better condition, suffer fewer failures and are only interfered with when they need maintenance, then it is possible that their lifetime could be increased. The reliability of the assets may be increased, resulting in fewer failures in the asset lifetime, but also the LCC of the railway infrastructure itself would be slightly reduced, because S&C components would not need to be replaced quite as often.

Capability	Opportunities for maintenance cost reduction
1	Reduced need to hold teams in readiness to react to failures
2	Reduced time on site when attending a faulty asset
3	Reduced or eliminated need for periodic inspection and maintenance tasks
4	Eliminated need for staff to prioritise and schedule work

Table 1 - Opportunities for reducing the cost of S&C maintenance

Table 1 summarises the opportunities which increased condition monitoring capabilities bring for reducing the direct costs of S&C maintenance. Each increase in capability brings a significant decrease in maintenance costs, as more decision-making ability is inherited by the automated system.

Level 1 capability gives maintenance teams advance warning of faulty operation. In some cases, the asset will continue to operate for some time after it has left the boundaries of normal operation, which means that there will be fewer occasions where teams have to be “scrambled” to attend on-site for emergency maintenance. Holding teams of technicians in readiness for emergency maintenance costs a lot of money, because staff are being employed to sit around waiting for something to go wrong.

[1] According to Deutsche Bahn (W. Grönlund)

Level 2 capability means that an automated system diagnoses faults and provides the information to the maintainers. Without this capability, staff often find it difficult to make an accurate diagnosis. This is borne out by the fact that in many cases, the most commonly reported cause of failure on switches is “no fault found”. By diagnosing faults automatically, staff can bring the correct tools with them to the site, knowing what tasks they need to perform, and do not have to spend a long time making examinations and attempting to diagnose the asset with only their senses to aid them.

Levels 3 and 4 bring the possibility of introducing a full Condition-Based Maintenance regime, *if and only if the automatic monitoring system is capable of detecting, diagnosing and identifying every possible failure mode of the asset.* Under CBM, there is no longer a need to carry out periodic maintenance, and the need for human inspection is reduced or eliminated, saving a very large amount of time and money. With level 4, this is further enhanced by the elimination of the need for maintenance staff to schedule and prioritise their work.

3.3.2 The need for a LCC assessment tool

It would be unrealistic to claim that the achievement of level 4 condition monitoring capability would completely eliminate the need for unplanned maintenance. It is undeniable that there are some faults in switch systems which simply cannot be predicted.

Additionally, it is well known that certain installations are more prone to certain types of fault than others, due to inherent properties which cannot be changed.

These two points lead to the conclusion that it is not necessarily economical to install the same level of condition monitoring capability on all switches throughout the network. A method for assessing benefits and costs is needed, so that the individual nature of each switch can be examined and the best condition monitoring solution can be chosen.

4 Calculating LCC benefits of using CM

4.1 Introduction

In this section, two approaches to calculating the financial benefits of condition monitoring are presented. The first is a straightforward estimation of the changes in life-cycle costs of an entire switch system. The second is a capability-based study of the costs and benefits of introducing different capability levels onto an existing asset; the costs modelled in this study are mostly savings due to reductions in delays.

The two models can be used together in order to correctly determine the course of action required for a particular asset case, based on the known failure statistics.

4.2 Life-cycle cost estimation

For the SP3.2 demonstrator installation in Eslöv, Sweden, a LCC estimation model was built in Microsoft Excel, to compare the life-cycle costs of the switch with and without monitoring. The individual worksheets are explained in the following sections.

4.2.1 The global input sheet

In the global sheet, data that does not need to be broken down in a product tree is registered. The time-dependent values for MTBF[2] and MTBM[2] can be given in either traffic tonnage or hours; the option for this must be chosen in the correct cell in order for the model to work correctly.

The global values can be filled in as constants or calculations. In this example, there is no difference between the values used for the cases with and without monitoring. Alternative values can be used by changing formulae elsewhere in the spreadsheet.

Some of the maintenance costs in this section are shown in Table 2.

[2] See glossary

Global no	Global heading	Type	Value	Normal	Invention
G1	Time	Period	N/A		
G2	Number of periods	Constant	40		
G3	Hours per year	Constant	8760		
G4	Zero value not allowed	Constant	0		
G7	Minutes per hour	Constant	60		
G8	Alternatives	Alternative	N/A	0	1
G9	Technical Life Time	Constant	40		
G10	Load factor	Constant	1		
G16	Load, T' [MGT/year]	Constant	20		
G18	Number of trains per	Constant	100		
G19	Time for installation [h]	Alternative	N/A	0	0
G20	Distance between site& p	Constant	0		
G25	No S&C Radius190-300m #	Alternative	N/A	0	0
G26	No S&C Radius500-600m #	Alternative	N/A	0	0
G27	No S&C Radius 760m[#]	Alternative	N/A	1	1
G28	No S&C Radius >760m[#]	Alternative	N/A	0	0
G31	Grinding cost/shift	Constant	24,000		
G32	Number of ground S&C/h	Constant	2		
G33	Preparation time grinding [h]	Constant	0.5		
G34	Grinding Interval [MGT]	Alternative	N/A	75	75
G35	Tamping cost/shift	Constant	32,000		
G36	Number of tamped S&C/h	Constant	1		
G37	Preparation time tamping [h]	Constant	0.2		
G38	Tamping Interval [MGT]	Alternative	N/A	100	150
G41	Length of a shift [h]	Constant	8		
G46	Train delay cost [€/min]	Constant	53		
G47	Work hour cost [€/h]	Constant	63		
G48	Number of persons per action	Constant	2		
G61	Inflation rate	Constant	0		
G62	Discount rate	Constant	4.0%		

Table 2 – Selected global costs

4.2.2 Train delay cost

Train delays are assumed to cost €53/minute. A more detailed model can be established if Monte Carlo simulation is used, but this was not implemented in this case study.

4.2.3 Investment cost

G150	Total Investment costs[€]	Alternative	N/A	0	0
G151	IN-Material cost [€]	Alternative	N/A	150,000	160,000
G152	IN-Transport cost [€]	Alternative	N/A	3,000	3,000
G153	IN-Installation cost [€]	Alternative	N/A	50,000	30,000
G154	IN-Preparation and planning [€]	Alternative	N/A	0	0

Table 3 - Initial costs

Table 3 shows the investment cost inputs; these can be inserted as a total in cell G150 or as separate portions in G151-3.

4.2.4 The time dependence of the model

There are two different time/load dependencies in the model. In G500 – G503 the global time dependence is given. The basic idea is that the failure rate (1/MTBF) and need for preventive maintenance (1/MTBM) will increase with global time because the total S&C will be in less good condition after several years of usage even if the maintenance is perfect. This assumes that the maintenance regime will still be, to a certain extent, periodic.

Tamping and grinding are assumed to be cyclic and therefore only dependent on yearly traffic load, but not on condition. Large-scale replacement is affected by this (G500). If no time dependence is wanted the figures should be 1.0. For linear time dependence the figure should be 2. It is recommended to have a figure of about 1.5; Sweden uses 1.3 for corrective maintenance (G501) and 1.6 for preventive maintenance (G502). G503 gives the MTBF in terms of load. In the case study it is stipulated that the S&C has been subjected to 200 Mt load during 20 years (T'_0=200/20= 10 Mt/year). Figure 6 shows a sketch of the MTBF model. Individual maintenance actions can be modelled as independent of global time, by setting β=1..

By looking in sheet "Period" a better understanding of these factors can be obtained.

G500	PPM Beta	Constant	1.6
G501	CM Beta	Constant	1.3
G502	PM Beta	Constant	1.6
G503	MTBF normal at T_0 Mt	Constant	200
G504	T_0' [Mt/year]	Constant	10

Table 4 - Time-dependent global values

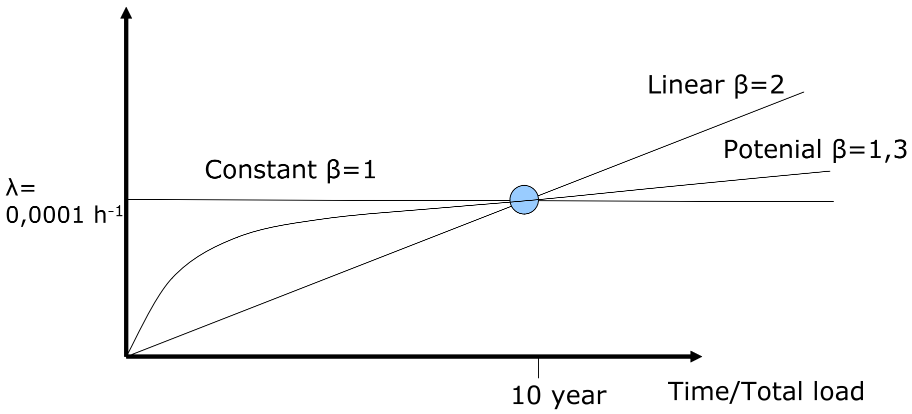

Figure 6 - Time-dependent MTBF models

The second time/load dependence is given by G504 and G16. It is assumed to be a linear relation between the actual load per year T' (G16) and T_0'. Using this model, all MTBF values are recalculated by the formula

$$MTBF_{actual} = MTBF \frac{T_0'}{T'}$$

(1)

4.2.5 Inspection cost

Inspection is described by number of visits per year, time spent per inspection (+ waiting time), number of persons involved and equipment cost. There are three types of inspections to be described: visual, geometry measurements and NDT. Working and waiting times are entered in minutes.

G550	Number of insp/year - Visual	Constant	6
G551	Number of insp/year -Measure	Constant	6
G552	Number of insp/year - NDT	Constant	0.1
G560	Time spent inspect -Visu	Constant	30
G561	Time spent inspect -Meas	Constant	10
G562	Time spent inspect -NDT	Constant	20
G570	Waiting time - Visual	Constant	30
G571	Waiting time -Measured	Constant	30
G572	Waiting time - NDT	Constant	120
G580	Number person - Visual	Constant	2
G581	Number person - Measured	Constant	2
G582	Number person - NDT	Constant	2
G590	Equipment cost - Visual	Constant	0
G591	Equipment cost -Measured	Constant	0
G592	Equipment cost - NDT	Constant	0

Table 5 - Inspection global values

4.2.6 Operation cost

Two different operational costs are included. This type of cost is not assumed to be time dependent:

- Heating
- Condition monitoring

If there is a wish to add more operational cost (snow clearance, cleaning, lubrication) it might be added in this section.

G593	Operational - Heating system [MWh/year]	Constant		2	1
G594	Operational cost - Heating system [€/MWh]	Constant		500	500
G595	Operational - Monitoring system [Manhour/year]	Constant			
G596	Operational - Monitoring system [€/Manhour]	Constant			

Table 6 - Global operating costs

4.2.7 Maintenance cost

Maintenance parameters are divided into corrective maintenance and preventive maintenance. The basic information is frequency (MTBF or MTBM), time spent (MTTR + MWT) and additional cost (material and equipment). This type of information is given on different types of maintenance actions and different subsystems.

A general calculation can be used in place of those for individual actions; a section is provided for this.

MTBF (and MTBM) can be entered as maintenance action after a certain time (hours) or after a certain traffic passing (traffic tonnage). If traffic is used as the input, this is converted into a value in hours. Table 1 shows the calculation for corrective maintenance actions.

Input mode	h	INPUT MTBF		Corrective Maintenance				
		MGT	h	MTBF [h]	MTTR	MWT	Equipment	Material
Control device	Adjust	52.1	45600	45600	0.25	1		
	Repair	2000	1752000	1752000	0.25	1		
	Replace	500	438000	438000	0.25	1		

Table 7 - Parameters for corrective maintenance

For corrective maintenance, the impact of delays is added by entering the delay minutes incurred per failure and the probability the failure will lead to a disruption of traffic. The model can be programmed to make the calculation dependent on the traffic load. This might be relevant to subsystems such as monitoring and heating.

Input mode	h			
		Train delay	Probability	Depends on MGT
Control device	Adjust	20	0.3	X
	Repair	20	0.3	X
	Replace	20	0.3	X

Table 8 - Train delay details and traffic dependence

For preventive maintenance there is one row that is treated differently. Large replacements (overhauls, for instance replacing a total crossing) are calculated to occur precisely according to the MTBM.

		INPUT MTBM		Preventive Maintenance				
		MGT	h	MTBM	MTTR	MWT	Equipment	Material
Control device	Adjust	15.1	13200	13200	3	1		
	Repair			0				
	Replace	250	219000	219000	4	1		
	Large replacement			0				
		MGT	h	MTBM	MTTR	MWT	Equipment	Material
Crossing	Adjust	11	9600	9600	3	1		
	Repair	65	56900	56900	6	1		
	Replace			0				
	Large replacement	140.9	123400	123400	30	1		24840

Table 9 - Preventative maintenance parameters

4.2.8 Input to invention sheet (the case with condition monitoring)

In the sheet Input Invention everything is initially copied from the normal case.

Yellow indicates there is no change in figure between the alternatives. Light green shows that the value has changed. By filling other values than 0% in the "Change" or "Depends on MGT" columns, the failure rate (maintenance action rate) is changed by the given amount.

		INPUT MTBM		Preventive Maintenance					
		MGT	h	MTBM	MTTR	MWT	Equipment	Material	Change
Control device	Adjust	15.1	13200	13200	3	1			0%
	Repair								0%
	Replace	250	219000	219000	4	1			0%
	Large replacement								
		MGT	h	MTBM	MTTR	MWT	Equipment	Material	Change
Crossing	Adjust	11	9600	9600	3	1			0%
	Repair	65	56900	56900	6	1			0%
	Replace								0%
	Large replac	112.72	98720	98720	30	1		24840	-20%

Table 10 - Inputs for the case where monitoring is included

4.3 Capability Evaluation Model

The 'Capability Evaluation Model' is a spreadsheet based tool for estimating the financial benefits of improved asset reliability, based on the introduction of different levels of condition-monitoring capability to a particular asset instance. The purpose of the model is to generate an accurate projection of costs and benefits over a selected discount period.

The model consists of three worksheets: the first represents RCM failure mode and detection statistics, the second holds the procurement, basic running costs and operational costs of the RCM system and the third displays the results of the analysis process in terms of projected costs and business benefit.

This model provides the following capabilities:

- Comparison of competing systems
- Comparison of the costs and benefits of installing different levels of capability
- Sensitivity analysis of the various factors associated with RCM investment

4.3.1 Capability analysis

The first stage of the evaluation model is to analyse the capabilities available for each possible failure mode. Different measurements of key parameters are required for the successful detection of particular failure modes. In addition, some failure modes cannot be predicted in advance by condition monitoring equipment.

Table 1 presents the resulting capability analysis for the top 25 failure modes of the 'HW' type switch actuator. The first column represents the failure modes of the asset taken directly from the capability matrix. The second column displays the occurrence of HW failures over a period of three years. The third column holds the delay minutes associated with each failure mode type. The fourth column holds a binary value indicating if the particular failure is detectable by the RCM system under investigation. This area of the worksheet represents the basic data that is required to initiate a cost benefit analysis.

Failure Mode	Frq.	Delay mins.	Potentially Detectable?	(%) Faults Detected	(%) Faults Detected Diagnosed	(%) Faults Diagnosed Identified	Potential Delay Minute Saving	Mins Saved (1)	Mins Saved (2)	Mins Saved (3)
Obstruction	1	100	1	75%	60%	80%	75	53	59	63
Detector rod OOA	4	426	0	0%	60%	80%	0	0	0	0
Drive rod OOA	8	2445	1	75%	60%	80%	1833.75	1284	1449	1537
Facing point lock OOA	7	878	0	0%	60%	80%	0	0	0	0
Drive rod OOA/G	7	12	1	50%	60%	80%	6	4	5	5
Detector rod OOA/G	1	10	0	0%	60%	80%	0	0	0	0
Facing point lock OOA/G	0	0	0	0%	60%	80%	0	0	0	0
Motor defective	2	85	0	0%	60%	80%	0	0	0	0
Stretcher bar fractured	19	84	1	70%	60%	80%	58.8	41	46	49
Motor worn/detached/out of tolerance	2	85	0	0%	60%	80%	0	0	0	0
Cutout reset not activated	2	12	0	0%	60%	80%	0	0	0	0
Motor high resistance	1	20	0	0%	60%	80%	0	0	0	0
Drive rod loose	7	12	1	70%	60%	80%	8.4	6	7	7
Snubber defective	1	19	0	0%	60%	80%	0	0	0	0
Detection assy. high resistance	1	68	0	0%	60%	80%	0	0	0	0
Drive rod loose/insecure	7	12	1	70%	60%	80%	8.4	6	7	7
Whole assy. high resistance	1	773	1	50%	60%	80%	386.5	271	305	324
Control circuit high resistance	1	19	0	0%	60%	80%	0	0	0	0
Motor electrical failure	1	30	1	80%	60%	80%	24	17	19	20
Detection assy. OOA/G	2	45	0	0%	60%	80%	0	0	0	0
Track hogged	0	0	0	0%	60%	80%	0	0	0	0
Schwihag rollers OOA	0	0	0	0%	60%	80%	0	0	0	0
Totals	**75**		8	**68%**			**2400.85**	**1681**	**1897**	**2012**
			Failures per annum		**% Failures Detected**					
			25		**16.875**					

Table 11 - Failure mode capability analysis sheet

To successfully evaluate the RCM system's ability to detect, diagnose and identify faulty behaviour a complete set of test data is required. To demonstrate the features of the model, some arbitrary values have been selected to represent the efficiency of each successive capability.

The column titled 'Faults Detected' is based on the analysis of the RCM system and its effectiveness in detecting faulty behaviour over a selected period.

The evaluation of the RCM system begins with the calculation of the potential delay minutes that can be saved for each failure mode. The 'Potential Delay Minute Saving' column holds the values representing the maximum amount of minutes that could be saved if the RCM was 100% effective based on the percentage of faults detected, i.e. if all faulty behaviour that could be detected were detected and acted upon before any failure occurred. For row 1 (Obstruction), the calculation is:

Delay Minutes x %Faults Detected = 100 x 75% = 75mins

(2)

However, since the RCM system is not 100% efficient, this value needs to be 'adjusted' to an appropriate level. The result of this adjustment is held in the column 'Minutes Saved (1)' in Table 11. In this example, a factor of 0.70 was used, i.e. in total 75% of all minutes can be saved and, of those minutes, 70% are saved through fault detection alone. For row 1 (Obstruction), the calculation is:

Potential Delay Minute Saving x Detection Efficiency = 75 x 0.7= 53

(3)

The 'Faults Detected Diagnosed' column represents the percentage of fault behaviour that the RCM system subsequently diagnosed. A system with the capability to detect and diagnose faulty behaviour is believed to have potential to increase the magnitude of the minute saving value. The column 'Minutes Saved (2)' in Table 11 represents, for this example, the increased value for a system that is capable of diagnosing a maximum of 60% of detected faults with an efficiency of 85%.

For row 1 (Obstruction), the calculation is:

(%Faults Detected Diagnosed x Potential Delay Mins x Diagnosis Efficiency)
+ (1 – %Faults Detected Diagnosed x Potential Delay Mins x Detection Efficiency)

(4)

Evaluating:

0.6 x 75 x 0.85 + (1 - 0.6 x 75 x 0.7) = 59

(5)

The 'Faults Diagnosed Identified' column represents the percentage of faulty behaviour that was detected, diagnosed and subsequently identified in time for action to be taken before a failure occurred. A system with the capability to detect, diagnose faulty behaviour and identify the time remaining to failure is believed to have potential to provide a further increase to the minute saving value. The column 'Minutes Saved (3)' in Table 11 represents, for this example, the increased value for a system that has the capability to identify a maximum of 80% of diagnosed faults with an efficiency of 95%. For row 1 (Obstruction), the calculation is:

(%Faults Diagnosed Identified x %Faults Detected Diagnosed x Potential Delay Mins x Identification Efficiency)
+ (1- %Faults Diagnosed Identified x %Faults Detected Diagnosed x Potential Delay Minutes x Diagnosis Efficiency)
+ (1- Faults Detected Diagnosed x Potential Delay Minute Saving x Detection Efficiency)

(6)

The result of this analysis is a set of figures that are unique to both the RCM system under study and the type of point machine. These figures provide a foundation for an analysis that supports a 'case for investment'. The next section discusses how these figures are used in a sample business case analysis.

4.3.2 Cost analysis

The main objective of the cost analysis is to assess the overall cost of the RCM system and offset these costs against the potential benefit taken from the capability analysis sheet. The procurement costs, which include figures for installation, approval and one off training costs (Table 12), are added to system specific running costs such as system support and maintenance (Table 13). The losses associated with the system through unnecessary maintenance interventions are also added to this cost, i.e. the rate of false alarms times the cost associated with intervention. Savings in the maintenance and life-cycle costs of the asset itself can be quantified in this section as well. These figures are arbitrary estimates.

Procurement Costs		Value
Capitol Cost		£150,000
Installation		£30,000
Regulatory Approval		£2,000
Training		£2,000
Power and comms (outlay)		£1,000
Total		**-£185,000**

Table 12 - RCM system procurement costs

Running Costs		Value
Power and comms (annual)		£1,000
Technical management		£1,200
Annual Maintenance		£2,000
Losses (false alarms * RCM prompted intervention)		£504
Total		**-£4,704**

Table 13 - RCM system running costs

The operational costs are specific to different areas and assessment methods used and as such provide the functionality to perform sensitivity analysis on the case for investment. This is shown in Table 14.

Operational Costs	Value
Elimination of hardlife maintenance costs	
Asset failure rate	25
Rate of false alarms	2.8
Delay minutes per RCM prompted intervention	0
Cost of unscheduled repair	£360
Cost of RCM prompted intervention	£180
Cost per minute of delay	£50
Minute saving per annum (1)	560
Minute saving per annum (2)	632
Minute saving per annum (3)	671
Costs saved per annum (1)	£28,010
Repair saving per annum (1)	£2,126
Total	**£30,136**
Costs saved per annum (2)	£31,611
Repair saving per annum (2)	£2,582
Total	**£34,193**
Costs saved per annum (3)	£33,532
Repair saving per annum (3)	£2,886
Total	**£36,417**

Table 14 - Operational costs

The ‘Asset Failure Rate’ represents the total number of failures for the studied period divided by the number of years in that period. The ‘Rate of False Alarms’ represents the number of times the RCM system prompted intervention when it was not required. The ‘Delay Minute per RCM Prompted Intervention’ is an additional cost to system prompted intervention. This figure is not implemented for points RCM as it is not considered that maintenance would usually cause a delay when inspecting a set of points. The ‘Cost of unscheduled repair’ is an assessment of the cost associated with sending a maintenance team to perform unscheduled maintenance on a failed asset. The ‘Cost of RCM prompted intervention’ is the cost associated with managing a maintenance resource to handle RCM related events. The ‘Cost per minute of delay’ is the cost associated with the per delay minute for the area that the RCM covers. This is one of the most important factors and can lead to significant variance in the cost benefit model. The ‘Minute saving per annum’ concept represents the total delay minutes saved and is provided from the capability analysis worksheet. There are three of these values based on the three levels of capability proposed in the capability matrix.

These figures are used to assess the long term return on investment for a particular RCM system for a set of points in a particular region. The next section shows how these values can be used to compare the long term benefit to be gained from RCM systems offering differing levels of detection and analysis.

4.3.3 Capability evaluation

The capability evaluation is based on a standard approach for modelling the future value of an asset. The net present value (NPV) method quantifies the benefit earned from an investment, as compared to the possible earnings expected if the initial outlay were instead invested on the stock market. The Present Value or PV of an asset at a set discount rate over a defined period is defined as

$$PV = -R_0 + \frac{R_t}{(1+i)^t} \tag{7}$$

Where

t is the time of the cash flow (generally in years)

i is the discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk.)

R_t is the net cash flow (the amount of cash, inflow minus outflow) at time t

R_0 is the initial cost

The Net Present Value for an investment is the sum of the PV terms for each year that the new asset is to operate. If it is positive, then the method suggests that the benefits of the investment outweigh the costs.

The figures produced from the NPV analysis are used to compare RCM systems and evaluate the case for investment in each. The following examples illustrate the improvement in return from systems that provide advanced analysis of faults. It should be noted that the procurement costs have not been increased to reflect these extended features. This reflects the fact that the hardware and equipment installation costs dominate; capabilities of level 2 onwards can generally be added in software with no extra deployment of hardware.

NPV case 1 – Fault Detection

For the purpose of this demonstration the selected discount rate is 8% over a period of 10 years. Note that the time frame starts from year ‘0’, i.e. there is no depreciation in the year of procurement. Figure 6 illustrates the result for the case where an RCM system is only capable of detecting faults (capability level 1). In this case, the NPV after ten years is a small negative number, indicating that there is no operating profit to be gained from making this investment *assuming that the condition monitoring system has a life of ten years*. However, this type of result may still lead to investment if there are other benefits to be gained, such as quality of service, reputation and asset life-cycle costs.

Year	0	1	2	3	4	5	6	7	8	9
NPV Factor	1	0.9259	0.8573	0.7938	0.7350	0.6806	0.6302	0.5835	0.5403	0.5002
Initial Procurement Cost	-£185,000									
Running costs	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704
Savings	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136
Total	-£159,568	£25,432	£25,432	£25,432	£25,432	£25,432	£25,432	£25,432	£25,432	£25,432
Present Value	-£159,568	£23,548	£21,804	£20,189	£18,693	£17,309	£16,027	£14,839	£13,740	£12,722
Net Present Value	-£159,568	-£136,020	-£114,216	-£94,027	-£75,334	-£58,025	-£41,999	-£27,159	-£13,419	-£697

Table 15 - NPV analysis for RCM capable of fault detection

NPV case 2 – Fault Detection and Diagnosis

Table 16 represents the NPV analysis for an RCM system, with similar outlay costs and overheads for the previous case, but with the ability to save $^1/_3$ of delay minutes (an arbitrary value for demonstration purposes) through fault detection and diagnosis. The savings arise through a decrease in delay minutes, although there is a slight increase in repair costs, since maintenance is now occurring before, rather than after, failure.

Year	0	1	2	3	4	5	6	7	8	9
NPV Factor	1	0.9259	0.8573	0.7938	0.7350	0.6806	0.6302	0.5835	0.5403	0.5002
Initial Procurement Cost	-£185,000									
Running costs	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704
Savings	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193
Total	-£155,511	£29,489	£29,489	£29,489	£29,489	£29,489	£29,489	£29,489	£29,489	£29,489
Present Value	-£155,511	£27,304	£25,282	£23,409	£21,675	£20,070	£18,583	£17,207	£15,932	£14,752
Net Present Value	-£155,511	-£128,207	-£102,925	-£79,516	-£57,840	-£37,770	-£19,187	-£1,981	£13,951	£28,703

Table 16 - NPV analysis for RCM capable of fault detection and diagnosis

With level 2 capability, the study shows a considerable improvement in benefit, with a positive NPV (an operating profit) achieved at the end of the 9th year (year 8) of ownership.

NPV case 3 – Fault Detection, Diagnosis and Identification

The third case, where faults are detected, diagnosed, and their severity identified, represents a small improvement on the previous case. A positive NPV is achieved at the end of the 8th year (year 7) of ownership providing a reasonable level of return on investment. The results are shown in Table 17.

Year	0	1	2	3	4	5	6	7	8	9
NPV Factor	1	0.9259	0.8573	0.7938	0.7350	0.6806	0.6302	0.5835	0.5403	0.5002
Initial Procurement Cost	-£185,000									
Running costs	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704
Savings	£36,417	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193	£34,193
Total	-£153,287	£29,489	£29,489	£29,489	£29,489	£29,489	£29,489	£29,489	£29,489	£29,489
Present Value	-£153,287	£27,304	£25,282	£23,409	£21,675	£20,070	£18,583	£17,207	£15,932	£14,752
Net Present Value	-£153,287	-£125,983	-£100,700	-£77,291	-£55,616	-£35,546	-£16,963	£244	£16,176	£30,928

Table 17 - NPV analysis for RCM capable of fault detection, diagnosis and identification

4.3.4 Sensitivity Analysis

The discount rate selected for projecting the future value of investment can vary depending on the type of investment. If a project is considered to be low risk then the discount rate may be lowered to reflect this. In the case where it is reduced to 6.5%, there is an improvement in the business case for a level 1 condition monitoring system, where a positive NPV is achieved in the final year of operation, as shown in Table 18.

Year	0	1	2	3	4	5	6	7	8	9
NPV Factor	1	0.9389	0.8816	0.8278	0.7770	0.7298	0.6853	0.6435	0.6040	0.6730
Initial Procurement Cost	-£185,000									
Running costs	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704	-£4,704
Savings	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136	£30,136
Total	-£159,568	£25,432	£25,432	£25,432	£25,432	£25,432	£25,432	£25,432	£25,432	£25,432
Present Value	-£159,568	£23,878	£22,421	£21,053	£19,761	£18,560	£17,429	£16,366	£15,361	£17,116
Net Present Value	-£159,568	-£135,690	-£113,269	-£92,216	-£72,455	-£53,895	-£36,466	-£20,100	-£4,739	£12,377

Table 18 - NPV analysis for RCM capable of fault detection with lower discount rate

5 Conclusions

Based on a functional analysis of a condition monitoring system's capability, two approaches for calculating the financial benefits of condition monitoring have been presented. The first is a straightforward estimation of the changes in life-cycle costs over an entire switch system (as considered by Banverket). The second is a capability-based study of the costs and benefits of introducing different capability levels onto an existing asset; the costs modelled in this study are mostly savings due to reductions in delays (as considered by Network Rail).

The two models can be used together in order to determine the course of action required for a particular asset case, based on the known failure statistics.

The capability evaluation model described in this document provides a platform for cost-benefit analysis to build tailored business cases for instances of assets which are being considered for the addition of condition monitoring equipment. The Net Present Value method provides an indicator for the profitability of each possible investment. It is possible to add other costs and savings to the calculation to strengthen the business case, such as the savings in maintenance costs achieved by working under a condition-based maintenance regime. This model is therefore a high-level tool which can be used to assist in decision-making for the allocation of condition monitoring resources and funds.