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A novel approach to diagnostic and prognostic evaluations applied to railways: A real case study

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Abstract

This paper presents qualitative and quantitative analyses of the action of points, a critical component of railway networks. They allow diagnostic and prognostic evaluations of the points using health monitoring systems, i.e. they allow the state of the system at a desired moment to be evaluated and the forecasting of the future condition of the system. The main objective is to increase the reliability, availability, safety and maintainability of these systems. A novel approach for maintenance management based on fault tree analysis is proposed. A binary decision diagram (BDD) approach is proposed for the qualitative analysis of the fault trees. The BDD obtains a Boolean expression for the fault tree. An optimal ordering of events is required in order to obtain an efficient conversion from a fault tree to a BDD, with the AND method being used for this purpose. Each event is classified based on its importance to the fault tree. It is studied using the Birnbaum and Criticality importance measures, using the Boolean expressions in order to perform accurate diagnostics and valuable prognostics on the state of the system. The presented approach allows the failure probability of the system to be determined along with importance measures obtained by considering variable time increments, e.g. shorter periods at the beginning and end of the life cycle of an event. A real case study on a set of M63 points is presented. The results provide useful information that can be used to support operations and the planning of maintenance tasks. The approach creates a methodology to establish effective maintenance planning, as it is a flexible and simple method that takes into account a nonlinear system that leads to an optimal allocation of resources. Finally, the conditions for an optimized online decision-making process are achieved.

Keywords

Maintenance management, Birnbaum, criticality, diagnostics, prognostics, fault tree, binary decision diagrams, point machine

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Introduction

A train can move from one track to another only at certain places and by using a mechanical device called a ‘turnout’. The turnout has moving parts, called switches (US: blades), which steer a train in one of two directions, normal (straight through) or reverse. The locking devices for the switch blades are used to ensure the correct and safe operation of points.

The research performed on the operation of points is insufficient if one considers the terrible consequences of a failure of a set of points, for example, the accidents at Eschede in 1998, Potters Bar in 2002 and Grayrigg in 2007. The objective of automatic detection,¹ failure analysis and diagnosis,² or wear assessment,^{3,4} is the use of condition monitoring equipment to analyse the various operating profiles, some of which can considerably vary when switching from either normal to reverse or reverse to normal directions, especially if faulty.^{2,5–8}

The operating force profiles of these mechanisms under even normal, fault-free operation are not particularly repeatable. Even from hour to hour, and certainly day to day, changes in environmental conditions (such as humidity or temperature) will mean that the profiles will differ from operation to operation. From month to month, continuously varying amounts of wear in the components, all of which may at particular maintenance intervals be lubricated, reset or replaced, means that one profile cannot be expected to be the exactly the same as another one.

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Figure 1. A set of points.

Approximately 55% of the failures of railway infrastructure components on high-speed lines occur on signalling equipment and turnouts. The term signalling equipment covers signals, track circuits, interlocks, automatic train protection (ATP) or track-loop-based ATP and the traffic control centre. The annual cost of maintaining points is high compared with other infrastructure elements, about £3,400,000 per year for about 1000 km of railway. TC-TCR trade circuits, for example, £2,100,000 per year for the same track length. The expenditure on points can be broken down into £1,200,000 for clamp-lock-type (hydraulic) turnouts and £1,400,000 for electrically operated turnouts (data provided by a UK asset manager).

Most standard point machines (see Figure 1) contain a switch-actuating system and a locking mechanism that includes a hand-thrown lever and a selector lever to allow operation by power or hand. The mechanism is normally divided into three major subsystems:

- the motor unit, which may include a contactor control arrangement and a terminal area;
- a gearbox consisting of spur-gears and a worm reduction unit with overload clutch;
- the dual control mechanism as well as a controller subsystem with motor cut-off and detection contacts.

Generally, there are also mechanical linkages for the detection and locking of the points. The standard set of railway points is therefore a complex electro-mechanical device with many potential failure modes.

The circuit controller includes detection switches and a pair of snap-action switches to stop the machine at the end of its stroke and to stop the motor so that the mechanism is not subject to impacts. The detection switches have high-pressure wiping contacts made of silver/cadmium oxide or gold and they are operated by both the lockbox and the detection rod. The detection switches have additional contacts to allow mid-stroke short-circuiting of the detection relays to avoid wrong indications in the signal box or electronic interlocking.

This paper proposed a novel approach to identify the critical components of the point mechanisms online, based on the probability of a fault of each component over a time period and the creation of a fault tree of the mechanism. The study is based on a real case study performed by a consortium consisting of Sheffield University (UK), Castilla-La Mancha University (Spain) and Balfour Beatty Rail (UK).

Fault tree analysis and binary decision diagrams

A fault tree (FT) is used a graphical representation of the logical relationships between the main elements of

the point machines. The FT considered in this paper consists of the following events and logic gates:

- the *top event* is the most undesirable event and it is allocated to the highest level of the tree;
- the *basic events* (e_i) are the basic faults and they are represented as a circle at the end of each fault;
- the *intermediate events* (g_i) are represented in the FT by rectangles that act as logic gates and they are used to connect events;
 - *AND gate*: the coexistence of all input events to this gate are required to produce the output event;
 - *OR gates*: at least one of the input events is necessary at these gates to produce the output event.

The analysis of a complex system can result in thousands of combinations of events, or cut-sets (CSs), that can cause the failure of a system. The determination of these CSs can be a large and time-consuming process,⁹ even for modern high-speed computers (NP-hard problem) and thus approximation techniques have been introduced in order to solve the problem with an inevitable loss of accuracy.¹⁰ In this paper a binary decision diagram (BDD) is proposed to obtain the probability of the top event of the FT.

Figure 2 presents a FT composed of seven non-basic events and nine basic events. It shows that the event e_7 is an important failure event as it is directly

related with the system failure, i.e. if e_7 occurs, a system failure will occur.

When the FT consists of a large number of events, there are various alternatives for a direct FT analysis. A direct analysis will be performed in this paper by use of a FT to BDD conversion.

BDDs were introduced by Lee¹¹ and popularized by Akers,¹² Moret¹³ and Bryant.¹⁴ It allows an analytical expression to be obtained that depends on the occurrence probability of every single basic event and the logical structure of the FT.¹⁵ Further information about BDDs can be found in Garcia and Escobar.¹⁶

Figure 3 shows the structure of the BDD obtained from the FT shown in Figure 2, it depends on the ordering of the events, that is to say, each different event ordering results in a different BDD.

The paths that start from the top event to a terminal 1 vertex provide a state in which a failure will occur. These paths determine the CSs, in this case 14 CSs (Figure 3). The probability of the top event (Q_{sys}) can be calculated as a function of the probabilities of the events (q_i) as follows

$$\begin{aligned}
 Q_{sys} &= CS_1 + CS_2 + \dots + CS_i + \dots + CS_n \\
 &= (q_7) + [(1 - (q_7)) \times (q_1) \times (q_3)] + [(1 - (q_7)) \\
 &\quad \times (q_1) \times (1 - (q_3)) \times (q_4) + \dots + CS_i + \dots \\
 &\quad + [(1 - (q_7)) \times (1 - (q_1)) \times (1 - (q_2)) \\
 &\quad \times (q_8) \times (1 - (q_9)) \times (q_5) \times (q_5)]
 \end{aligned}$$

Figure 2. An example of a FT.

Figure 3. An example of a BDD.

The size of the BDD and the CPU runtime depend on the ordering of the variables. Different ranking methods can be used to reduce the number of CSs, and consequently, to reduce the CPU runtime.^{17,18} There is no direct method that can be used to create the minimum size of the BDD in all cases. The ordering method to rank the events that is used in this paper is the AND method, a heuristic approach that orders the variables based on the number of AND gates and the relations between them.¹⁹

Diagnostic-based maintenance

Diagnostics concerns the evaluation of the state of a system at a certain time. It is performed in this paper using importance measures (IMs) to rank events and to show their relative importance to the top event probability. The IM methods used are the Birnbaum and Criticality approaches.^{16,20,21}

The Birnbaum IM provides a value for the relationship between the probability of a system failure and an event. It is defined as follows

$$I_i^{Birn} = \frac{\partial Q_{sys}}{\partial q_i}$$

where I_i^{Birn} is the Birnbaum IM value of event i . It represents the probability that the system is in a critical state such that the occurrence of event i causes a system failure, Q_{sys} is the probability of the

occurrence of the system failure and q_i is the probability of the occurrence of event i .

Figure 4 shows the Birnbaum importance value obtained for each event using the probabilistic values given in Appendix 1, together with the FT described in Appendix 2. The FT was obtained from a previous research project performed by one the current authors.⁵⁻⁷ There is no previous context in which to explain the data set calculated in this paper using a simulation approach, as the objective of this paper is to propose a novel methodology to analyse and optimize the prognostics, diagnostics and maintenance tasks. There is an important difference between the IMs of the events. It is recommended to use diagnostics tasks to identify events with a higher importance as this will lead to an increase in the accuracy of the diagnostics and, consequently, improved assignment of facilities to maintenance tasks, optimized costs, an increased reliability, etc.

The main disadvantage of using the Birnbaum IM approach is that it does not consider the probability of an event, i.e. it overstates the importance of events with a low probability of occurrence (called rare events).

Criticality IM takes into account the occurrence probability of events, defined as

$$I_i^{Crit} = \frac{q_i}{Q_{syst}} \times \frac{\partial Q_{syst}}{\partial q_i} = \frac{q_i}{Q_{syst}} \times I_i^{Birn}$$

Figure 4. Static Birnbaum IM.

Figure 5. Static Criticality IM.

where I_i^{crit} is the Criticality IM of event i . It represents the probability that event i is critical for the system and that the event occurs when the system has a failure. In addition, q_i is the probability assigned to event i and Q_{sys} is the probability of the occurrence of a system failure.

Figure 5 shows the Criticality IM of all the events using the input probabilistic values from Appendix 1 and the FT shown in Appendix 2.

The differences between Figures 4 and 5 are due to the probabilities of the occurrence of the events. In Figure 5, rare events are not taken to be major events. The rare events can be identified by evaluating the difference between the Birnbaum and Criticality IMs. The quantitative results of an analysis of the IM are only used to classify the events, and these are then used for prognostic evaluation and diagnosis of the system.

Prognostic-based maintenance

Prognostic-based maintenance allows the anticipation of the occurrence of a fault. The objective in this paper is to support the management of maintenance actions by providing the necessary information in order to schedule maintenance tasks.

The probability functions for each event are:¹⁶

- constant probability

$$q_i(t) = K, \text{ where } K \text{ is a constant, } K \in [0, 1];$$

- exponential increasing probability

$$q_i(t) = 1 - e^{-\lambda t}, \quad \lambda > 0;$$

Figure 6. The dynamic probability for each event.

- linear increasing probability

$$q_i(t) = mt, m > 0, \quad mt < 1;$$

$$q_i(t) = 1, m > 0, \quad mt \geq 1;$$

- periodic probability

$$q_i(t) = 1 - e^{-\lambda(t-n\alpha)}, n = 1, 2, 3, \dots, \lambda > 0, \text{ and } \alpha > 0$$

determines the period.

Appendix 3 shows the values assigned to the parameters of the probability functions for each event listed in Appendix 1. Figure 6 plots the probability distribution of a fault for each event as a function of time. These data were randomly generated for each event in order to be able to perform simulations of the state of the system as a function of time, however, the probability functions were set by the authors after considering the engineering interpretation of each event. For example, the event e2 is considered to be a linear increasing probability of occurrence over time, as it is assumed that wear is constant, and e11 has a constant probability, i.e. oversized holes or undersized bolts always have the same size. These functions allow the probability of the failure system as a function of time to be calculated using a FT approach. It is important to note that in this paper, the probability function for each event is not optimal. The probability function of each event should be obtained by condition monitoring, statistical analysis, etc. The main purpose is to present an approach for analysing the Q_{sys} by considering a stochastic system.

The fault probability of the top event will increase over time if maintenance actions are not performed, according to the data shown in Figure 6. An event with an occurrence probability assigned as being periodic is set to zero in each period. Figure 7 plots the probability function of the top event as a function of

time; it displays a general rising trend. The reason why it is not always rising is due to the events with a periodic probability function. This probability was obtained for 50 samples. The curve in Figure 7 can be used to perform a prognostic evaluation, to fit the operations thresholds, etc.

The dynamic analysis proposed in this paper can facilitate the creation of effective maintenance planning based on the probability of a system failure over time. This means that the reliability of the system can be maintained.

This paper uses the IMs in order to classify events based on their relevance in determining the state of the top event at a certain time. Figure 8 shows the Birnbaum IMs calculated for all samples and all the events detailed in Appendix 2. It allows the critical events at each time point to be identified and these can be considered in the diagnostics and prognostics procedures. For example, the event e120 shows a low Birnbaum IM value compared with the event e59. The difference between them grows over time, i.e. the event e59 is more critical for system operation.

The most important information from this study is the ranking of the events as a function of time, this allows a diagnostic analysis of the state of the top event, e.g. it helps operators to optimize maintenance tasks and the relevant costs as they now know the critical events occurring at a particular point in time.

The methodology used in this paper allows the time increment to be a variable. This feature can be useful when the system needs to be studied in detail at specific time points.

Figure 9 shows the Criticality IM for all the events, considering the probability of an event at each point in time. Different trends can be observed, e.g. the event e59 initially presents a rising curve

Figure 7. The dynamic probability for system failure.

Figure 8. The dynamic Birnbaum IMs.

Figure 9. The dynamic Criticality IM.

Figure 10. The dynamic Criticality IM.

that subsequently falls. However, the event e120 presents a constant trend. When an event is analysed, the probabilities of the remaining events are less important than is the case for the Birnbaum IM.

The Birnbaum and Criticality IMs are complementary; however, there is no conclusion about which of them is the better one. It will depend on whether the event has to be analysed using the topology of the tree, where the Birnbaum IM is used. The Criticality IM is recommended in cases where the event needs to be studied in terms of the probability of the event and the system, together with the topology. If rare events need to be analysed, the Criticality IM should be used.

Preventive maintenance strategy

The approach proposed in this paper provides quantitative results that facilitate diagnostic and prognostic tasks. The diagnostic tasks are performed by setting the condition of the system and identifying the critical components. The objective of prognostics is to determine the state of the system at a certain point in time.

The information provided by IMs (see Figures 4 and 5) is used in a diagnostic task. For the case of a system failure, the events that make a major contribution to the probability of a system failure can be identified. The data shown in Figure 5 allow the components to be classified based on their importance and a priority ranking of events to be established.

This approach leads to the development of dynamic preventive maintenance planning. The

results provided by the dynamic analysis allow the tasks to be assigned based on the reliability of the system. The approach presented in this paper consists of the following steps

1. Set a threshold that determines the maximum allowed level of unavailability.
2. Determine the cut-off point between the system failure probability and the established threshold.
3. Identify when a certain system failure probability is reached.
4. Determine the most important events at the critical cut-off point.
5. Assign maintenance tasks based on these events in order to maximize the reliability of the system.

Figure 10 shows the probability of a system failure as a function of time, where the unavailability threshold is represented by the horizontal dashed line, the cut-off point is marked with a circle and the failure probability (horizontal line) at a certain time is given by the vertical dashed line. It corresponds to the 13th sample in Figure 10.

Figure 11 presents a cross-section of Figure 9 at the 13th sample, where the most influential events are highlighted.

Table 1 classifies the events into three groups, A, B and C, based on their importance. This classification is not necessarily constant, i.e. the size of the groups depends on the amount of resources to be allocated and the reliability that is required to be obtained. This flexibility allows an optimized online decision-making

Figure 11. The dynamic Criticality IM.

Table 1. Classification of events based on their importance (see Figure 11).

Group	Scope	Number of events	Events
A	3% more important events	5	e59, e36, e81, e71, e110
B	15% more important events	20	A & e35, e37, e38, e46, e47, e57, e60, e68, e70, e79, e84, e108, e109, e111, e112
C	25% more important events	35	A & B & e41, e44, e45, e54, e55, e58, e69, e72, e76, e77, e78, e82, e83, e113, e114

process to be developed by automatically choosing the correct number of events. The nonlinearity of the system can lead to more events than necessary being chosen when a specific reduction in the system failure probability is required.

The occurrence probability of an event is reduced to zero when it requires a maintenance action. Figure 12 shows the probability of system failure as a function of time. This probability decreases depending on the components requiring repair. The number of events taken into account determines the period of time that the system will be below the threshold. This leads to the decision-making problem being solved dynamically as the criteria can change over time. Figure 12 was obtained using a variable time increment: from zero to 10, the time increment is five times bigger than the increment used from 10 to 23. This is an important advantage because the critical zone (dashed square) can be analysed in fine detail.

The reduction in the system failure probability obtained in the 14th sample by the event set A, B and C is 13.38, 24.06 and 38.15%, respectively (see Figure 12).

Conclusions

A novel quantitative FT analysis of a set of points was performed in order to set diagnostic and prognostic tasks. A FT was used in a real case study of a M63-type set of points; the logical interactions between main events or components were considered in detail. The values of the probability of the occurrence of an event were set following advice from area experts. Then a quantitative analysis was performed using a BDD. The AND method was used to rank the events. A BDD is an acyclic structure that allows the probability of failure of the points to be obtained by taking into account all the possible alternatives that could lead the system to fail. BDDs are used because

Figure 12. Applying a maintenance strategy.

they provide an analytical expression of the system failure probability in a reasonable computation time, they consider the probabilities of basic events, and they allow dynamic simulations, e.g. the calculation of the IMs as a function of time. The flexibility of the approach allows a dynamic analysis with a variable time increment and thus a detailed study of a specific period of time, e.g. for any failure distribution that could be used, a shorter increment at beginning and end of the life cycle of the event.

The Criticality IM gives useful information for diagnosis tasks. It presents the probability of an event, stating if it is critical for the system and that the event occurs when the system has failed. The IM allows the diagnosis of the system.

The system failure probability over time was used to set maintenance strategies in order to keep the probability under a desired threshold. A dynamic analysis of the IMs was used to create a maintenance plan that contributes to improved decision-making by optimizing resources. A case study of this approach was presented, and a reduction of 13.86% was obtained by considering 3% of the events. The classification is flexible, i.e. the size of the groups of events depends on the resources to be allocated. This flexibility allows the development an optimized online decision-making process that considers the nonlinear nature of the system.

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Appendix I

The events descriptions and occurrence probabilities

The events descriptions and occurrence probabilities are listed in Table 2.

■■■.

Event	Event description	Prob (%)	Event	Event description	Prob %
Top	M63 point failure		e102	7/8" pin worn	50
g1	Civil & environmental		e103	Broken rollers	25
g2	Civil		g41	Backdrive 3	
g3	Vibration		e104	Bush wear	50
e1	Voiding	50	e105	Broken damaged roller stocks	25
e2	Damage/wear	50	e106	Broken stretcher	10
e3	Broken chog bolts	50	e107	Broken worn cranks	10
e4	Stud bolts fouling	10	g42	Rail clamp locks	
e5	Broken base plates	50	g43	Rail clamp locks I	
e6	Fittings become loose	5	g10	Environment	
g4	Track geometry		g11	Environment I	
e7	Cant	5	e28	Broken clutch springs. Broken clutch contact, spring mechanism	5
e8	Track complexity	50	e29	Diode block faulty direction	5
e9	Radius	10	e30	Clutch slip current set-up	5
g5	Condition of track		e31	Seized clutch	1
g6	Condition of track I		g12	Environment 2	
e10	Track gauge wide/road spread	10	e32	Diode plug not fully inserted	1
e11	Oversized holes/undersized bolts	5	e33	Worn clutch assembly	1
e12	Uneven switch rail contact on all chairs	25	e34	Clutch restraint screw coming out, should be a bolt	1
e13	Twist faults	1	g2	Civil	
e14	Switch crippled	10	g3	Vibration	
g7	Condition of track 2		e1	Voiding	50
e15	Stock rail moving	10	e2	Damage/wear	50
e16	Hogging	25	e3	Broken chog bolts	50
e17	Dry/rusty chairs	50	e4	Stud bolts fouling	10
e18	Missing components	5	e5	Broken base plates	50
e19	Yellow slide chair scoring	10	e6	Fittings becoming loose	5
g8	Condition of track 3		g4	Track geometry	
e20	Sole plate wear	4	e7	Cant	5
e21	Movement loose fish plates	5	e8	Track complexity	50
e22	Wrong components fitted	1	e9	Radius	10
e23	Loose slide chairs	10	g5	Condition of track	
g9	P-way working alone		g6	Condition of track I	
e24	Lift & pasking	10	e10	Track gauge wide/road spread	10
e25	Pulling in road	50	e11	Oversized holes/undersized bolts	5
e26	Tamper damage	25	e12	Uneven switch rail contact on all chairs	25
e27	Chair bolts fouling switches	10	e13	Twist faults	1
g10	Environment		e14	Switch crippled	10
g11	Environmental		g7	Condition of track 2	
e28	Broken clutch springs. Broken clutch contact, spring mechanism	5	e15	Stock rail moving	10
e29	Diode block faulty directional	5	e16	Hogging	25
e30	Clutch slip current set-up	5	e17	Dry/rusty chairs	50
e31	Seized clutch	1	e18	Missing components	5

(continued)

Continued

Event	Event description	Prob (%)	Event	Event description	Prob %
g12	Environment 2		e19	Yellow slide chair scoring	10
e32	Diode plug not fully inserted	1	g8	Condition of track 3	
e33	Worn clutch assembly	1	e20	Sole plate wear	4
e34	Clutch restraint screw coming out should be a bolt	1	e21	Movement loose fish plates	5
g13	Uneven traffic patterns		e22	Wrong components fitted	1
g14	Uneven traffic patterns 1		e23	Loose slide chairs	10
e35	Lateral movement of track	5	g9	P-way working alone	
e36	Infrequent operation mechanism	10	e24	Lift & pasking	10
e37	Flat tyre damage	1	e25	Pulling in road	50
g15	Uneven traffic patterns 2		e26	Tamper damage	25
e38	Stock rail burns	25	e27	Chair bolts fouling switches	10
e39	Grooved slides	5	g44	Uneven traffic patterns	
e40	Switch creep	50	g45	Uneven traffic patterns 1	
e41	Dry chairs uneven lubrication	25	e108	Stock rail burns	25
g16	Machines		e109	Grooved slides	5
g17	Machines 1		e110	Switch creep	50
g18	M63 drive		e111	Dry chairs uneven lubrication	25
g19	Drive external to machine	50	g46	Uneven traffic patterns 2	
e42	Worn drive lug bolt	1	e112	Lateral movement of track	5
e43	Loose drive shoe	10	e113	Infrequent operation mechanism	10
e44	Machine loose	5	e114	Grooved slides	1
e45	Loose drive basket	10	g47	Rail clamp locks 2	
e46	No clearance between stretcher & rail kicking	1	g48	Clamp lock	
e47	Nuts run back on drive	10	g49	Pump unit	
g20	Motor		g50	Pump unit 1	
g21	Motor 1		e115	Defective pump	1
g22	Motor 11		e116	Vibration loosens 2BA nuts	1
e48	Motor defects	1	e117	Leaky tank	1
e49	Worn brushes	10	e118	Sticking valve	10
e50	Motor wiring plug high resistance	1	g51	Pump unit 2	
e51	Dirty motor cam	5	e119	Worn brushes 'HR'	25
e52	Lightly loaded brushes	1	e120	Frozen pump unit	1
g23	Snubbing	15	e121	Earthed motors	1
e53	Diode open-circuit	25	g52	Mechanics	
e54	Snubbing resistor burnt out	50	g53	Mechanics 1	
e55	Burnt snubbing contacts	25	e122	Loose fixed cam	1
e56	Motor brushes high resistance	25	e123	Burnt/worn damaged hoses/pin holes in hoses	25
g24	Motor 2		e124	Wrong lock arm fitted	1
g25	Motor 21		e125	Broken crimps/terminals	50
e57	Clutch	7,5	e126	Tie bar adjustment/too long/drilling wrong	10
e58	Sticky brushes 2	1	e127	Displaced ferrule in adapter block	1
e59	Broken OP spring braid	5	g54	Mechanics 2	
e60	Earthed motor	1	e128	Leaky rams	10
g26	Motor 22		e129	Dirt, grease build-up on mechanisms	1
g27	Springs	15	e130	Centre thrust packing wrong	25
e61	Burnt springs	25	e131	Loose Allen screws	10
e62	Spring adjustment	50	e132	Switch assembly bushes worn	5

(continued)

Continued

Event	Event description	Prob (%)	Event	Event description	Prob %
e63	High-resistance 'H' piece	25	e133	Faulty micro-switches	25
g28	Cutout contact	15	g55	Mechanics 3	
e64	Seized crank handle contacts	5	e134	Tuning fork wear	25
e65	Operators not resetting cut out	50	e135	Point heater strip fouls body	1
e66	High resistance cut out contact	50	e136	Loose/no spiral fitted	1
g29	Drive internal to machine		e137	No adjustment for wear	5
g30	Drive internal to machine 1		e138	Lock sticking, mark I only	5
e67	Failure to drive insufficient throw	5	e139	'O' rings missing from rams	5
e68	Broken drive rod spring trailing points	1	g56	Mechanics 4	
e69	Broken/worn worm drive	1	e140	Worn or missing nibs, mark I only	1
e70	Crank handle operation sticking	1	e141	Loose body	25
g31	Drive internal to machine 2		e142	Open switch tappet adjustment	10
e71	Change drive belt/lose ball bearings	1	e143	Poor cover seals	1
e72	Snubbing problems bolt breaks	5	e144	No lock wires in hoses 5.2.19	1
e73	Poor design of throw bar coupling lug serrations	5	e145	Loose cabling no glands	1
e74	Snubbing adjustment	5	g38	Backdrive	
g32	M63 detection		g39	Backdrive 1	
e75	Circuit controller springs	5	e94	Lack of 50 mm Flangeway	25
e76	4 foot lock detector arrangements	1	e95	Nuts run back	50
e77	Seized detection effects external fittings	1	e96	Obstructions weeds/growth	1
e78	No lift on push rod & push rod wear	1	e97	Obstruction ballast	25
g33	M63 lock		e98	Loose fittings	50
e79	Effects from temperature	25	g40	Backdrive 2	
e80	Restrictive adjustment of lock manufacturer's design	1	e99	No escarpment on supplementary drive	50
e81	Lack of fine adjustment floating lock	1	e100	Shoes broken/loose	25
e82	Worn lock dog	1	e101	Unsupported channel rod	25
e83	Seized lock rod/nuts	5	e102	7/8" pin worn	50
e84	Lock blade binding on machine case	1	e103	Broken rollers	25
g34	Machines 2		g41	Backdrive 3	
g35	Supplementary detection		e104	Bush wear	50
g36	Supplementary decision I		e105	Broken damaged roller stocks	25
e85	Chaffed cable/wire missing/incorrectly fitted cable glands	1	e106	Broken stretcher	10
e86	Loose mounting plate	25	e107	Broken worn cranks	10
e87	Centre stud running loose	1	g57	S&T standars	
e88	Faulty micro-switch	25	g58	S&T standars I	
e89	Blocked drain holes/wear seal in lid	1	e146	4-port pump	10
g37	Supplementary detection 2		e147	Float & fixed lock convention	10
e90	BR detector wrong blades	1	e148	No differential N&R. Also F&B ports	10
e91	Loose/missing packers	5	e149	SMSs need to improve	10
e92	Lack of stroke inadequate maintenance	25	e150	Component design	10
e93	Tamped	1	e151	4-port pump unable to do correspondence	10
g38	Back drive		g59	Training	
g39	Back drive I		g60	Training I	
e94	Lack of 50 mm flangeway	25	e152	Poor maintenance	10

(continued)

Continued

Event	Event description	Prob (%)	Event	Event description	Prob %
e95	Nuts run back	50	e153	Difficulty fault finding on supplementary detectors	10
e96	Obstructions weeds/growth	1	e154	Equipment incorrectly fitted	10
e97	Obstruction ballast	25	e155	M63 machines special tools needed for set -up	10
e98	Loose fittings	50	g61	Training 2	
g40	Backdrive 2		e156	Equipment incorrectly maintained	10
e99	No escarpment on supplementary drive	50	e157	'O' ring incorrectly fitted in supplementary detector on replacement of micro-switch	10
e100	Shoes broken/loose	25	e158	Difficulty in identifying 'run through'	10
e101	Unsupported channel rod	25	e159	RLC lock slide inaccessible	10

Appendix 2

FT for a M63 type set of points
The FT for a M63 type set of points is shown in Figure 13.

16 Figure 13. ■■■.

Appendix 3

Parameters of the probability functions

The parameters of the probability functions are shown in Table 3.

Table 3. The parameters of the probability functions.

Event	K	λ	m	θ	Event	K	λ	m	θ
e1	0.02	0	0	0	e81	0.07	0	0	0
e2	0	0	0.03	0	e82	0	0.023	0	0
e3	0	0.02	0	0	e83	0	0	0.01	0
e4	0	0	0.08	0	e84	0.05	0	0	0
e5	0	0.5	0	0.3	e85	0	0	0.02	0
e6	0	0	0.01	0	e86	0	0	0.02	0
e7	0.01	0	0	0	e87	0	0	0.03	0
e8	0.05	0	0	0	e88	0.02	0	0	0
e9	0.1	0	0	0	e89	0.02	0	0	0
e10	0.1	0	0	0	e90	0.02	0	0	0
e11	0.05	0	0	0	e91	0.03	0	0	0
e12	0.01	0	0	0	e92	0.08	0	0	0
e13	0	0	0.02	0	e93	0	0	0.04	0
e14	0	0.03	0	0	e94	0.05	0	0	0
e15	0.01	0	0	0	e95	0	0	0.05	0
e16	0	0	0.05	0	e96	0.052	0	0	0
e17	0	0.6	0	0.4	e97	0.02	0	0	0
e18	0	0	0.04	0	e98	0	0.2	0	0.15
e19	0.01	0	0	0	e99	0	0	0.05	0
e20	0	0	0.021	0	e100	0	0	0.06	0
e21	0	0	0.02	0	e101	0.04	0	0	0
e22	0.005	0	0	0	e102	0.06	0	0	0
e23	0	0	0.03	0	e103	0	0.23	0	0.22
e24	0.04	0	0	0	e104	0.04	0	0	0
e25	0.02	0	0	0	e105	0	0.4	0	0.15
e26	0	0	0.041	0	e106	0	0.3	0	0.26
e27	0	0	0.01	0	e107	0	0.5	0	0.4
e28	0	0.01	0	0	e108	0.04	0	0	0
e29	0	0	0.01	0	e109	0.04	0	0	0
e30	0.05	0	0	0	e110	0	0.04	0	0
e31	0	0	0.01	0	e111	0.04	0	0	0
e32	0	0	0.02	0	e112	0.05	0	0	0
e33	0	0.01	0	0	e113	0.021	0	0	0
e34	0.05	0	0	0	e114	0.025	0	0	0
e35	0.05	0	0	0	e115	0	0	0.05	0
e36	0.06	0	0	0	e116	0.2	0	0	0
e37	0	0	0.03	0	e117	0	0	0.05	0
e38	0.04	0	0	0	e118	0	0	0.063	0
e39	0	0	0.04	0	e119	0	0.6	0	0.23
e40	0	0	0.01	0	e120	0.3	0	0	0
e41	0.025	0	0	0	e121	0.08	0	0	0
e42	0	0	0.01	0	e122	0.09	0	0	0
e43	0.01	0	0	0	e123	0	0	0.04	0
e44	0	0.015	0	0	e124	0.047	0	0	0
e45	0	0	0.012	0	e125	0	0.01	0	0

(continued)

Table 3. Continued

Event	K	λ	m	θ	Event	K	λ	m	θ
e46	0.05	0	0	0	e126	0	0.03	0	0
e47	0.05	0	0	0	e127	0	0.05	0	0
e48	0	0.4	0	0.3	e128	0	0	0.02	0
e49	0	0	0.08	0	e129	0.041	0	0	0
e50	0.04	0	0	0	e130	0.04	0	0	0
e51	0	0.4	0	0.5	e131	0.05	0	0	0
e52	0.03	0	0	0	e132	0	0	0.02	0
e53	0.01	0	0	0	e133	0	0	0.02	0
e54	0.054	0	0	0	e134	0.06	0	0	0
e55	0.045	0	0	0	e135	0.06	0	0	0
e56	0.01	0	0	0	e136	0.2	0	0	0
e57	0.04	0	0	0	e137	0.5	0	0	0
e58	0.02	0	0	0	e138	0.5	0	0	0
e59	0	0	0.07	0	e139	0.04	0	0	0
e60	0	0.35	0	0.15	e140	0	0.55	0	0.2
e61	0	0	0.01	0	e141	0	0	0.01	0
e62	0	0	0.04	0	e142	0.04	0	0	0
e63	0.02	0	0	0	e143	0.2	0	0	0
e64	0.03	0	0	0	e144	0.3	0	0	0
e65	0.014	0	0	0	e145	0	0.06	0	0
e66	0.02	0	0	0	e146	0.01	0	0	0
e67	0.01	0	0	0	e147	0.01	0	0	0
e68	0	0	0.03	0	e148	0.01	0	0	0
e69	0	0	0.014	0	e149	0.01	0	0	0
e70	0.045	0	0	0	e150	0.01	0	0	0
e71	0.052	0	0	0	e151	0.01	0	0	0
e72	0	0	0.02	0	e152	0.01	0	0	0
e73	0.01	0	0	0	e153	0.01	0	0	0
e74	0.01	0	0	0	e154	0.01	0	0	0
e75	0	0	0.01	0	e155	0.01	0	0	0
e76	0.02	0	0	0	e156	0.01	0	0	0
e77	0.03	0	0	0	e157	0.01	0	0	0
e78	0.03	0	0	0	e158	0.01	0	0	0
e79	0	0	0.032	0	e159	0.01	0	0	0
e80	0.03	0	0	0					