Maintenance strategies: Decision Making Grid vs Jack-Knife Diagram

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Abstract

Purpose – Maintenance management is a vital strategic task given the increasing demand on sustained availability of machines. Machine performance depends primarily on frequency and downtime; therefore, ranking critical machines based on these two criteria is important to determine the appropriate maintenance strategy. The purpose of this paper is to compare two methods, using case studies, to allocate maintenance strategies while prioritising performance based on frequency and downtime or Mean Time to Repair: the Decision Making Grid (DMG) and Jack-Knife Diagram (JKD).

Design/methodology/approach – The literature indicates the need for an approach able to integrate maintenance performance and strategy in order to adapt existing data on equipment failures and to routinely adjust preventive measures. Maintenance strategies are incomparable; one strategy should not be applied to all machines, nor all strategies to the same machine.

Findings – Compared to the Pareto histogram, the DMG and JKD provide visual representations of the performance of the worst machines with respect to frequency and downtime, thus allowing maintenance technicians to apply the appropriate maintenance strategy. Each method has its own merits.

Research limitations/implications – This work compares only two methods based on their original conceptualisation. This is due to their similarities in using same input data and their main features. However, there is a scope to compare to other methods or variations of these methods.

Practical implications – This paper highlights how the DMG and JKD can be incorporated in industrial applications to allocate appropriate maintenance strategy and track machine performance over time.

Originality/value – Neither DMG nor JKD have been compared in the literature. Currently, the JKD has been used to rank machines, and the DMG has been used to determine maintenance strategies.

Keywords Maintenance management, Decision Making Grid, Jack-Knife Diagram

Paper type Research paper

1. Introduction

1.1 Problem statement

The vast majority of maintenance models are aimed at answering efficiency questions, for example, "How can this particular machine be operated more efficiently?" They are not aimed at effectiveness, for example, "Which machine should we improve and how?" (Vanneste and van Wassenhove, 1995; Kobbacy *et al.,* 1995; Cho and Parlar, 1991). Yet, practitioners are often interested in the latter question and are dissatisfied if a model is directly applied to an isolated problem. In an integrated approach to maintenance, efficiency analysis (do the thing right) should be preceded by effectiveness analysis (do the right thing). The Decision Making Grid (DMG) (Labib, 2004) and the Jack-Knife Diagram (JKD) (Knights, 2001) can work together to address this issue.

Maintenance costs and downtime depend on two factors: downtime frequency and downtime length or Mean Time to Repair (MTTR). Pareto histograms, traditionally used to prioritise failure codes, consider only one downtime criterion, typically MTTR, and are

unable to analyse the two criteria simultaneously. In addition, according to Knights (2004), Pareto analysis has a number of deficiencies.

First, as a Pareto histogram is usually based on downtime (or cost) alone, it cannot determine which factor(s) predominate in the downtime or costs associated with particular failure codes.

Second, Pareto histograms for failure codes ranked according to repair cost, equipment downtime, failure frequency and MTTR will generate four distinct lists of failure code priorities. A graphical means of simultaneously visualising equipment availability, reliability and maintainability problems as a function of equipment failure codes would be useful.

Third, Pareto analysis of equipment downtime may not identify individual events with high associated downtimes or frequently occurring failures consuming relatively little downtime whilst causing frequent operational disturbances.

Fourth, when there are many data to analyse, data stratification or hierarchical decomposition techniques are commonly used. There are two potential problems with the use of stratified Pareto analyses: because hierarchical Pareto graphs are only prepared for the significant contributors of system downtime, failures associated with less significant components or functional failures are not explored; and the same failure mode may appear in several of the lower level Pareto histograms.

In contrast, the DMG and JKD provide a single display that ranks failure codes according to the two important downtime factors, frequency of downtime and MTTR. Maintenance strategies are incomparable; that is, not all maintenance strategies are applicable to all failure codes. The DMG and JKD have the added advantage of allocating the appropriate maintenance strategy depending on the position of a machine according to these two downtime factors. In short, both provide a better means of establishing maintenance priorities.

DMG and JKD are alike in their reliance on mapping failure frequency and downtimes. Whilst the DMG acts as a map on which the performances of the worst machines are located according to multiple criteria, the JKD is a logarithmic scatterplot enabling failures to be classified according to acute or chronic characteristics. The object is to implement appropriate actions leading to the movement of machines towards improvement in these criteria (Labib, 2004).

1.2 Performance measures and maintenance strategies

There is a gap between the literature and practice in understanding the effectiveness of maintenance performance measures and their impact on maintenance strategies and decision making. The majority of the literature promotes performance measures as a vital instrument that links strategies and management decisions with the execution of improvement initiatives (Neely *et al.*, 2005; Kaplan and Norton, 1992). More specifically, in the area of maintenance, much literature emphasises the importance of maintenance performance measurements (Parida and Chattopadhyay, 2007; Simoes *et al.*, 2011; Kumar *et al.*, 2013).

Currently, the software packages for maintenance management are either called computerised maintenance management systems (CMMSs) or enterprise resource planning (ERP) systems with the current market leader being SAP software. CMMSs are dedicated to the management of maintenance in both corrective and preventive modes. ERP systems, formerly called material requisition planning, rely on using a unified database management system that integrates maintenance to other functions in the business; specifically, those related to logistics such as spare parts management. However, such systems usually run without making full use of the data from the CMMS/ERP system. In addition, such software packages tend to be used for data analysis and facilitating exchange of reports rather than for offering real decision support, see Labib (2003) for criticism of CMMSs.

There is an indication that when making decisions, maintenance managers tend not to rely on the key performance indicators and their data in the CMMS. For example, empirical

research by Muchiri *et al.* (2010) casts doubt on the utility of maintenance performance measurement in terms of its impact on decisions taken. They find a relatively small number of decisions and changes are triggered by performance measurements. In fact, a significant number of maintenance managers are not satisfied with their performance measurements (Muchiri *et al.*, 2010).

An early paper empirically investigating the link between maintenance strategies and performance finds a strong positive relationship between pro-active and aggressive maintenance approaches (e.g. total productive maintenance (TPM) or reliability-centred maintenance (RCM)) and performance (Swanson, 2001). An empirical investigation of the relationship between business and maintenance strategies by Pinjala *et al.* (2006) says quality competitors tend to have more pro-active maintenance policies than others. In a survey of maintenance practices, Alsyouf (2009) concludes that there is a need for more frequent adoption of such maintenance concepts as TPM and RCM.

In terms of selection of maintenance strategy, Labib *et al.* (1996) and Labib *et al.* (1997) suggest using the multiple criteria decision making technique of the analytic hierarchy process (AHP). Bevilacqua and Braglia (2000) also advocate AHP. Al-Najjar and Alsyouf (2003) propose a conceptual model using fuzzy logic and multiple criteria to select cost effective maintenance approaches; Wang *et al.* (2007) suggest a model for the selection of maintenance strategies using the fuzzy variation of AHP. Oyarbide-Zubillaga *et al.* (2008) use discrete event simulation to optimise preventive maintenance (PM); Picciolo *et al.* (2008) use Markov modelling to optimise periodic inspection. To select a maintenance strategy more generally, Bashiri *et al.* (2011) propose using a fuzzy linear assignment method, whilst Pourjavad and Shirouyehzad (2014) propose the fuzzy analytic network process (ANP). In more specific analyses, Lazakis and Olcer (2015) advocate a fuzzy multiple attribute group approach to select a maintenance strategy in the maritime industry, and Nakhjavani *et al.* (2014) suggest a hybrid approach using both ANP and the decision making trial and evaluation laboratory (DEMATEL) method to select the optimal maintenance strategy in the pharmaceutical industry.

The above literature indicates the need for an approach able to integrate maintenance performance and maintenance strategy, one able to adapt to existing data on equipment failures and to routinely adjust preventive measures.

The DMG and JKD models have received little attention in the literature, yet they have the potential to routinely analyse data captured in CMMS and to aid decision makers in the implementation of performance-enhancing maintenance strategies. Their visual representation of machine performance is an appealing feature distinguishing them from other approaches. Their ability to prioritise machine downtime based on two criteria (frequency and length of downtime) has already been noted. In addition, their ability to classify maintenance strategies enables the allocation of the different responsibilities of preventive measures across machine groups. Such an approach is useful to the decision maker, first to plan the implementation of appropriate strategies and then to monitor their impact.

In the literature, ELECTRE-SORT is a sorting method able to consider an unlimited number of criteria in order to assign machines to incomparable strategies (Ishizaka and Nemery, 2014). The main drawback of ELECTRE-SORT is its complexity. In cases where a decision needs to be taken quickly, either the DMG or the JKD is sufficient. We limit the concept of maintenance to these two approaches because they are the most commonly used in the industry, and they address both aspects of maintenance in terms of being system-based (RCM), or human-based (TPM).

2. The DMG
The DMG acts as a map on which the performances of the worst machines are located according to multiple criteria. The DMG model was initiated by Labib (1996). During subsequent research,

it was integrated into CMMS by Labib (1998), into AHP by Labib *et al.* (1998a) and into fuzzy logic by Labib *et al.* (1998b). It has since become widely implemented in the industry (Fernandez, *et al.*, 2003; Labib, 2004; Burhanuddin *et al.*, 2007; Tahir *et al.*, 2008; Shahin and Attarpour, 2011; Aslam-Zainudeen and Labib, 2011; Tahir *et al.*, 2014; Mc Leod *et al.*, 2015).

In the DMG, assets are plotted on two separate dimensions: downtime and failure frequency. Downtime is commonly represented by the key performance indicator, MTTR, whilst failure frequency is often represented as mean time between failures (MTBF); an increase in failure frequency equals an increase in the reciprocal of MTBF. Some argue that the DMG is insufficient as the consideration of only two criteria does not necessarily result in a wise decision; it has been suggested, for instance, that cost should be included as well. However, cost as a dimension is already captured if we consider cost to be analogous to downtime, with both seen as measures of severity (Labib, 2014).

The concept of the DMG enables the user to determine when to apply TPM- or RCM-based approaches. Figure 1 is adapted from Labib (2004) who states: "The significance of this approach is that rather than treating RCM and TPM as two competing concepts it unifies them within a single analytical model".

The DMG comprises nine sections, each of which is represented by one of five different maintenance strategies. The asset's position on the grid determines the accompanying optimum maintenance strategy. Note that the DMG refers to PM as fixed time maintenance (FTM) instead. This is done on purpose in order to avoid confusion with TPM when referring to it in the DMG model. Note that CBM is used in the DMG to signify "predictive maintenance", which is defined in the Maintenance Terminology Standards (BSI 13306) as "Condition-based maintenance carried out following a forecast derived from the analysis and evaluation of the significant parameters of the degradation of the item" (Figure 2).

The objective is to implement actions leading to the movement of the asset's performance towards the top left section representing low failure frequency and low downtime (Labib, 2004). Contributions towards classifications using greater than two maintenance criteria include ELECTRE-SORT, developed by Ishizaka and Nemery (2014), group dominance-based rough set approach (DRSA), developed by Chakhar *et al.* (2016), and application of DRSA in classification of maintenance spare parts (Hu *et al.*, 2017). However, more research is needed to optimise the number of categories and demonstrates their practical applicability.

2.1 DMG strategies

The allocation of maintenance strategies to various machines is analogous to prescribing drugs for different patients. In the field of medicine, two extremes may occur, i.e. prescribing one drug to all patients and prescribing all drugs to one patient, are neither feasible nor acceptable.
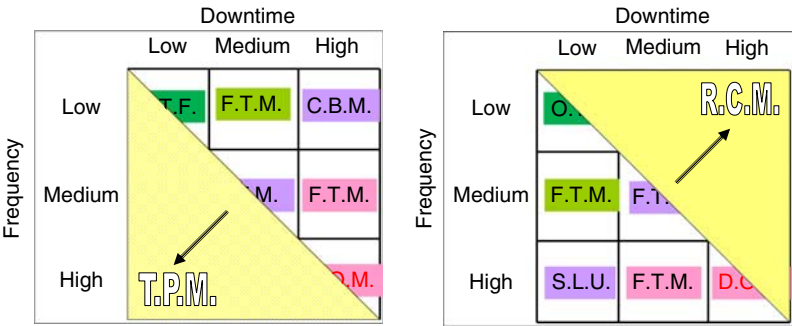

Figure 1.
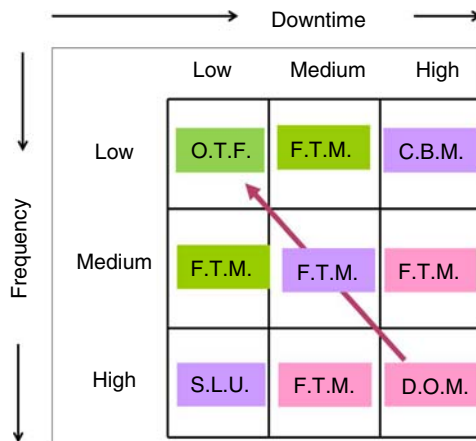When to apply RCM and TPM in DMG (Labib, 2004)

Figure 2.
Decision Making
Grid asset strategies
(Labib 2004)

The same applies in maintenance: one strategy should not be applied to all machines, nor all strategies to the same machine.

Five maintenance strategies are presented below; the strategy "prescribed" for a specific failure code depends on the failure's location in the DMG.

Operate to failure (OTF). Assets falling in the top left-hand section of the grid represent machines with low failure frequency and low downtime. This is the optimal state and is the area of the grid towards which all asset performance figures should aspire. In this case, the suggested strategy, OTF, sustains the best practice for the machines concerned. Note that OTF does not imply ignoring the asset but rather to audit sustainability of the existing best practice.

Skills level upgrade (SLU). When breakdowns occur frequently but are fixed quickly resulting in little downtime, the SLU strategy should be used. One of the underpinning elements of TPM is the transfer of some basic maintenance skills from maintenance technicians to the front-line operators in production, hence the term "productive maintenance" (Nakajima, 1988; Hartmann, 1992; Willmott, 1994). As mentioned earlier, chronic losses ("death by a thousand cuts") should be dealt with using TPM-type initiatives. For example, menial tasks such as machine resetting or minor adjustments can be carried out by operators once they have received the correct training, i.e. SLU. Another variation of SLU is to de-skill the maintenance function on a machine by focusing on improving its maintainability.

Condition-based maintenance (CBM). Assets with low frequency of failure but high downtime when failures (infrequently) occur call for CBM. Such assets can have catastrophic failures resulting in extended downtime ("show stoppers"). By monitoring their condition with such techniques as thermographics and vibration analysis, maintenance departments should be able to pre-empt failures and proactively enact measures to avoid downtime. For a review of CBM, see Jardine *et al.* (2005). This investigative strategy follows the RCM concept, a term coined by Nolan and Heap (1979) and widely disseminated by Moubray.

Design out maintenance (DOM). The bottom right-hand section of the grid represents the worst performing assets in both criteria. Major design out projects need to be considered for any machines in this section. An asset in this quadrant is considered not fit for purpose, and hence it should be a candidate for next shut down, overhaul or turnaround activities.

FTM. The FTM sections bordering OTF near the top left-hand section represent "easy" FTM. Issues of PM include who will carry out the work and when. The FTM sections bordering DOM in the bottom left-hand section are frequently seen as "difficult" FTM. The PM issues to be addressed here relate to the actual contents of the jobs.

According to Labib (2004), the above-mentioned strategies are arranged in ascending order with respect to either cost or perceived benefits. Put otherwise, the benefit or cost of maintenance strategies are as follows: OTF < FTM < SLU < CBM < DOM.

2.2 Methods of setting thresholds in the DMG
There are three methods to create partitions between low, medium and high frequency and downtime. The first method, introduced by Fernandez *et al.* (2003), is to subtract the lowest values from the highest values, divide by three and multiply by two. Let h be the highest value in the list and l the lowest value in the list. Then:

$$\text{Medium/High boundary} = h - \frac{1}{3}(h) \tag{1}$$

$$\text{Low/Medium boundary} = h - \frac{2}{3}(h) \tag{2}$$

$$\text{Low boundary} = l \tag{3}$$

This method is used when data are homogeneous, and there is an almost equal number of machines in every category. However, if data are not homogeneous, i.e. there is a large discrepancy in the values, the second method is more applicable.

The second method by Tahir *et al.* (2009) is based on the concept of clustering. The idea is to set partitions at maximum difference by sorting the data in descending order, subtracting the following value from each value in the column and setting the partition at the maximum difference. In other words, let H be the highest value in the list and let n be the equivalent machine. Then:

$$\text{Medium/High boundary} = \text{Max}(H_n - H_{n-1}) \tag{4}$$

The same procedure is followed for every partition.

The third method is to use fuzzy sets as proposed in Labib *et al.* (1998b) by setting membership functions for each category based on the judgments of the decision maker. In this method, the idea is to determine membership functions that are either triangular or trapezoidal in order to represent the three categories of low, medium and high for both downtime and frequency domains. Fuzzy logic can then be implemented to compute the allocated resources to spend on each strategy. As DMG already contains a set of nine rules (in its 3×3 matrix), combining this with the membership functions allows the formulation of a fuzzy logic approach based on three steps: fuzzification, rule evaluation and defuzzification.

3. JKD
The use of the JKD was initiated when Knights (2001) and Knights (2004) applied it to prioritise the unplanned downtime data for electrical failures in a fleet of 13 cable shovels at an open pit copper mine in Northern Chile. In a more recent study, Jardine and Tsang (2013) use the JKD to prioritise the downtime of 695 minor components for a fleet of 14 mobile assets in an underground mine. For their part, Pascual *et al.* (2009) extend the JKD technique of considering three key performance indicators, reliability, maintainability and unavailability, to include explicit economic effects. Finally, Wijaya *et al.* (2010) visualise failure data by using interval estimation instead of point estimation in a JKD.

Maintenance downtime of a system during a given period of time T, due to an intervention code denoted as Downtime$_j$, is the product of the number of times, n_j, that this

code occurs and the mean time to repair, MTTR$_j$, of the system, expressed as:

$$\text{Downtime}_j(T) = n_j(T) \cdot \text{MTTR}_j(T) \qquad (5)$$

If all codes are displayed in an n vs MTTR diagram, it is possible to discriminate those codes causing the major downtimes; it is also possible to assess whether the downtimes are related to a high frequency of being out of service. A disadvantage of using Equation (5) is that curves of constant downtime, known as iso-downtime curves, are hyperbolae (Pascual *et al.*, 2009; Knights, 2001; Knights, 2004). A solution is to take the logarithm of Equation (5), written as:

$$\log\left(\text{Downtime}_j(T)\right) = \log\left(n_j(T)\right) + \log\left(\text{MTTR}_j(T)\right) \qquad (6)$$

where log refers to $\log_{10}$. When an x-y graph is prepared of log n_j against log MTTR$_j$, the iso-downtime curves become straight lines with a negative gradient. Logarithmic scatterplots simplify the identification of those failures contributing most to total equipment downtime or cost, whilst permitting the visualisation of the influence of failure frequency and mean downtime.

3.1 Limit determination
When assessing failures, it is necessary to differentiate between chronic and acute problems. Threshold values are determined by relative values that depend on the relative magnitude and quantity of data. Repairs requiring lengthy downtime are considered acute problems. Frequently reoccurring failures (i.e. high n) are considered chronic problems. By determining the threshold limits, the log scatterplot can be divided into four quadrants as shown in Figure 3. To be consistent with the axes of the DMG, the JKD axes are flipped, with frequency plotted on the y-axis rather than on the x-axis; note that the latter is the more common configuration in the JKD literature. The lower quadrants denote chronic failures, whilst the right-hand quadrants denote acute failures. The lower right-hand quadrant is a region of acute and chronic failures.

The total downtime, D, caused by unplanned failure is:
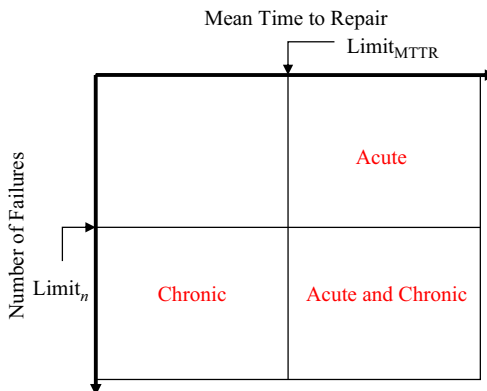
$$D_j = \sum_j \text{Downtime}_j \qquad (7)$$

Figure 3.
Schematic of JKD showing regions of importance

and the total number of failures, N, is:

$$N = \sum_j n_j \tag{8}$$

When Q represents the number of distinct failure codes used to categorise the repair data, the threshold limit for acute failures can be defined as:

$$\text{Limit}_{\text{MTTR}} = \frac{D}{N} \tag{9}$$

and the threshold limit for chronic failures becomes:

$$\text{Limit}_n = \frac{N}{Q} \tag{10}$$

3.2 Downtime priorities and the business cycle
Maintenance priorities are based on the economic consequences of failures and the associated repair costs. The economic consequences of a failure include the opportunity cost of lost production, the extension of fixed costs such as operator salaries which must be paid irrespective of equipment downtime, the cost of maintaining an increased number of spares as a result of the failure, and the cost of maintaining redundant equipment to mitigate the effects of possible lost production.

In some industries, the economic consequences of plant or equipment downtime for critical equipment outweigh repair and maintenance costs. In such circumstances, it is desirable to prioritise production costs (i.e. equipment availability and reliability) over repair costs. In such a case, where:

Cost of lost production $> >$ repair and maintenance costs,

the region of concern is the shaded area in Figure 4.

The availability limit, the line of constant downtime, equals to the product of the two threshold limits calculated in Equations (9) and (10) and is expressed as:

$$\left\{ \begin{array}{ll} n_i \times \text{MTTR}_i = \frac{D}{Q} & \text{where } 0 < n_i < \text{Limit}_n \\ n_i = \text{Limit}_n & \text{where } n_i \geqslant \text{Limit}_n \end{array} \right\} \tag{11}$$
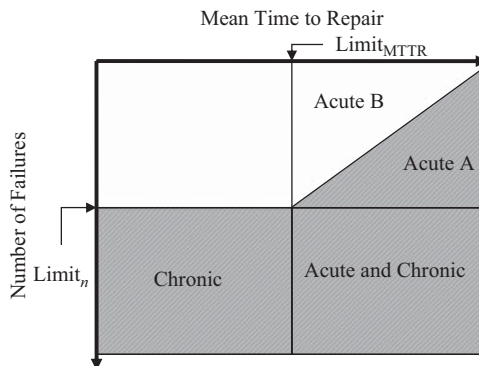

Figure 4.
JKD when it is desirable to prioritise production over repair costs

In the case of commodity price troughs, the cost of production becomes more significant; controlling and reducing O&M costs will be as important as maintaining equipment and availability. Here, the region of concern is shown in Figure 5, and the expression of the availability limit is:

$$
\left\{
\begin{array}{ll}
\text{MTTR}_i = \text{Limit}_{\text{MTTR}} & \text{where } 0 < n_i < \text{Limit}_n \\
n_i \times \text{MTTR}_i = \frac{D}{Q} & \text{where } n_i \geqslant \text{Limit}_n
\end{array}
\right\}.
\tag{12}
$$

According to Knights (2001), greater benefits are obtained by preventing the reoccurence of a single acute failure than by preventing the reoccurence of a chronic failure. Hence, all acute failures should remain in the priority area. The JKD on which this paper focuses is represented in Figure 5. After categorising failure codes, a prioritised list may be developed, similar to the maintenance strategies in the DMG, as follows:

Unclassified < chronic B < chronic A < acute < acute and chronic

Once a prioritised list of failure codes is identified, hypotheses can be made about the possible cause (or causes) of each problem. Root causes of equipment downtime are associated with the following broad categories; equipment design, purchase, storage, installation or start-up, operation and maintenance. Chronic repairs are often associated with design problems, inappropriate operator practices or poor quality control in upstream processes.

An advantage of the JKD over the DMG is that the position of machines/components relative to threshold lines is clear, but this is also due to having only two partitions in the JKD as compared to three partitions in the DMG. According to Knights (2001) and Knights (2004), the JKD can be used as a "trend plot" to visualise the trends in maintenance performance over several time periods. In the first study, Knights (2001) observes improvements in two failure codes over the period of the study: Lubrication and Cabin. Unplanned failures to the shovel's lubrication system are classified chronic in 1997 and 1998 but appear in the unclassified region in 1999. In addition, the total downtime caused by a failure of control in the operator cabin decreases over the period. Two other failure codes go in the opposite direction: unplanned failures in swing system fall into the acute region in 1997 but appear in the acute and chronic region in 1998 and 1999. Likewise, failures linked to alarm increase in both duration and frequency, going from unclassified in 1997 to chronic in 1998.

4. Examples
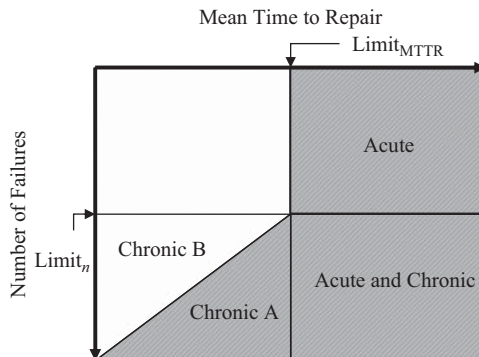The three examples given in this section compare the DMG to the JKD.

Figure 5.
JKD when repair costs are as important as maintaining equipment availability and reliability

4.1 Example 1

Aslam-Zainudeen and Labib (2011) prepare a DMG using data on a fleet of Class 319 trains from First Capital Connect, a train operating company that operates in the South of the UK. This data will be used to plot the JKD and compare to the DMG. Based on the criteria in Table I, the DMG and JKD are shown in Figures 6 and 7, respectively. For the JKD limits, based on the data in Table I and Equations (9) and (10), $D = 861$ minutes, $N = 56$, $Q = 10$, $Limit_{MTTR} = 15.375$, and $Limit_n = 5.6$. Figure 7 shows the rounded values for the limits.

In the DMG, machines whose performance is located in the top-right section of the grid, the CBM square, are problematic. They may not break down very often (low frequency) but they represent a major, long-lasting problem when they do (high downtime). A similar region in the JKD is the acute region. In the DMG, no components appear in the CBM region, but in the JKD, I and E appear in the acute region. For I and E, the JKD seems pessimistic. Upon closer inspection of the location of I and E in the JKD relative to the axes, we find E has a medium frequency of failure with high MTTR, which is the same characterisation as in the DMG. However, I has a high MTTR with low frequency, a pessimistic finding compared to its classification in the DMG.

	Frequency	No. of failures	Criteria 1 (DMG)		Downtime	Delay minutes	Criteria 2 (DMG)
A	Power	18	High	B	Doors	268	High
B	Doors	13	High	A	Power	225	High
C	Safety systems	5	Medium	E	Brakes	122	High
D	Air systems	5	Medium	C	Safety systems	68	High
E	Brakes	4	Medium	F	Current collection equipment	51	Medium
F	Current collection equipment	4	Medium	D	Air systems	34	Medium
G	Interior seats, floor and trims	3	Low	I	Train communication	32	Medium
H	Jumpers and coupling	2	Low	G	Interior seats, floor and trim	28	Low
I	Train communication	1	Low	H	Jumpers and coupling	25	Low
J	Underframe	1	Low	J	Underframe	8	Low

Table I.
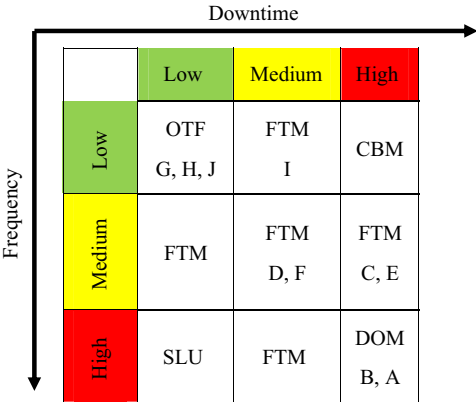Criteria analysis of class 319 trains for DMG

Figure 6.
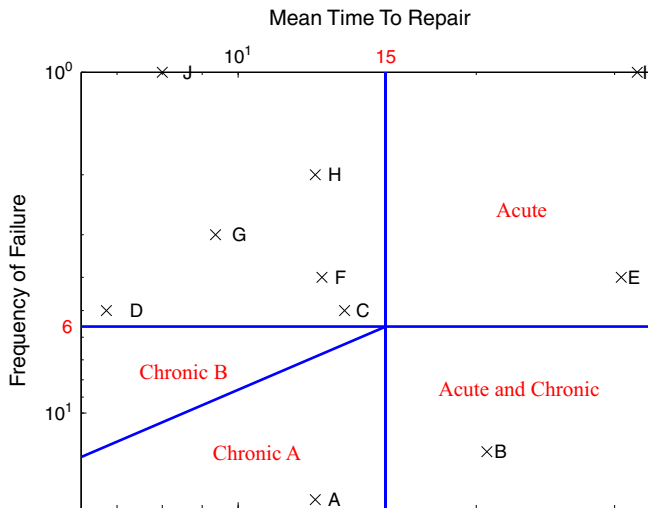Decision Making Grid for example 1

Figure 7.
Jack-Knife Diagram
for example 1

According to the DMG, the appropriate strategy for A and B is DOM. However, the JKD does not classify A as Acute & Chronic. OTF components, according to the DMG, are G, H and J, which also fall in the unclassified region of the JKD along with F, C and D, although they are close to the boundaries. The performance of these components will need close monitoring over time.

4.2 Example 2
Table II presents unplanned downtime data for electrical failures in a fleet of 13 cable shovels, collected over a one-month period, at an open pit copper mine in Northern Chile (Knights, 2001). For DMG mapping, Table II allocates codes to low, medium and high groups for each criterion according to Equations (1)-(3) (Figures 8 and 9).

Code	Description	Criterion 1 (DMG)	Downtime (minutes)	Criterion 2 (DMG)	Code	Frequency
"1"	Electrical inspections	High	1,015	High	"11"	36
"2"	Damaged feeder cable	High	785	High	"1"	30
"11"	Motor overtemperature	High	745	High	"3"	27
"3"	Change of substation or shovel move	High	690	High	"9"	26
"10"	Overload relay	High	685	High	"10"	23
"7"	Auxiliary motors	Medium	600	Medium	"5"	21
"12"	Earth faults	Medium	575	Medium	"2"	15
"8"	Main motors	Medium	555	Medium	"4"	15
"5"	Power cuts to substations	Medium	395	Medium	"7"	13
"15"	Air compressor	Medium	355	Medium	"8"	12
"6"	Rope limit protection	Low	277	Low	"6"	10
"9"	Lighting system	Low	240	Low	"13"	9
"4"	Coupling repairs or checks	Low	225	Low	"15"	8
"17"	Overcurrent faults	Low	220	Low	"12"	7
"14"	Control system	Low	165	Low	"14"	7
"16"	Operator controls	Low	155	Low	"17"	6
"13"	Miscellaneous	Low	115	Low	"16"	5

Table II.
Low, medium and high allocation, for each criterion, for DMG mapping of unplanned shovel electrical downtime
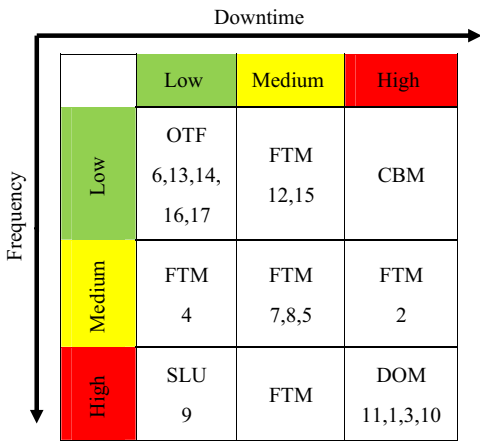
Figure 8.
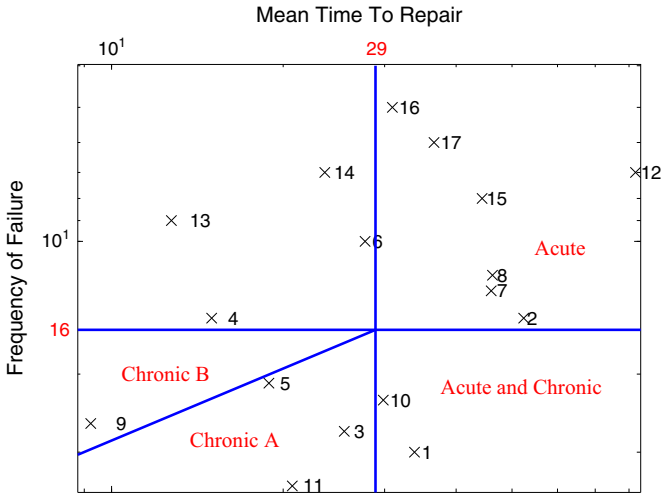Decision Making Grid
for example 2

Figure 9.
Jack-Knife Diagram
for example 2

Components in the OTF section in the DMG and the unclassified region in the JKD will be discussed first. The diagrams' overlapping codes are 6, 13 and 14. In the DMG, 4 falls in the mid-left-hand section of the grid but is unclassified in the JKD (although very close to $Limit_n$ border); in the JKD, 17 appears in the acute region but is in the OTF grid in the DMG. The advantage of the JKD here is that the availability of a visual representation of the proximity of a failure code to either the $Limit_n$ or $Limit_{MTTR}$ borders.

A seemingly big difference between the DMG and the JKD is the classification of 17. In the DMG, 17 is of little concern and should operate as normal to failure. However, the JKD classifies this component as acute. If closer attention is paid to the axes of the JKD, the frequency of failure for component 17 is low, and its MTTR is midway. For 17, the JKD is pessimistic.

Now, looking at the DOM section of the DMG and the acute and chronic grid of the JKD, the overlapping codes are 1 and 10, respectively. In the DMG, components 3 and 11 also fall in the DOM grid but appear only in the Chronic A region of the JKD. In this case, the

DMG is pessimistic. In the JKD, 3 is closer to the $\text{Limit}_{\text{MTTR}}$ border and should be monitored closely over time. Again, the advantage of the JKD is that we can see how far components are from the borders.

4.3 Example 3

Table III provides a list of scheduled and unscheduled breakdowns for a Geomembrane plant in 2007. Figures 10 and 11 show the corresponding DMG and JKD plots for the data in Table III.

In Figure 10, D falls in the DOM section of the grid, with E, F, I and J in the OTF section. In the JKD, D falls in the acute and chronic region, a classification similar to that of the DMG. No components require CBM according to the DMG. G is classified as acute in the DMG, and

Code	Description	Frequency	Criterion 1 (DMG)	Code	Downtime (minutes)	Criterion 2 (DMG)
"D"	Flat T-Die 2,400 mm	88	High	"G"	7,080	High
"A"	Vacuum loading system	87	High	"D"	5,820	High
"C"	(i) Gear box (single helical gear type) Output speed = 58 RPM (ii) Extruder (120 Ø screw) (iii) DC driving motor 55 kW and 1,150 RPM	53	Medium	"A"	4,620	Medium
"H"	Cooling unit	53	Medium	"C"	3060	Medium
"B"	(i) Gear box (single helical gear type) Output speed = 58 RPM (ii) Extruder (120 Ø screw) (iii) DC driving motor 75 kW and 1,150 RPM	52	Medium	"B"	2640	Medium
"G"	Winding system	43	Medium	"H"	2640	Medium
"E"	Emboss, polishing and cooling rolls system	41	Low	"E"	1440	Low
"I"	Air compressor	40	Low	"I"	1320	Low
"J"	Overhead crane	40	Low	"J"	840	Low
"F"	Take-up system	39	Low	"F"	600	Low

Table III.
High, medium and low classification for DMG
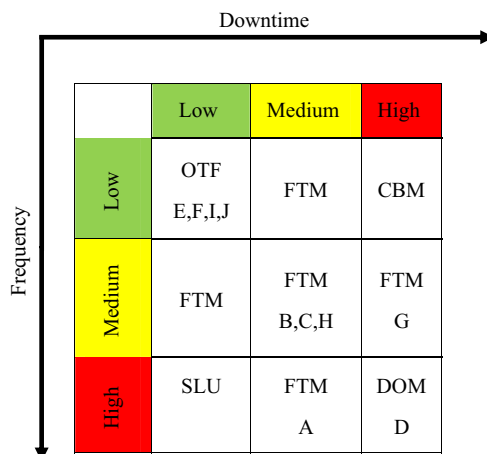
Figure 10.
Decision Making Grid for example 3
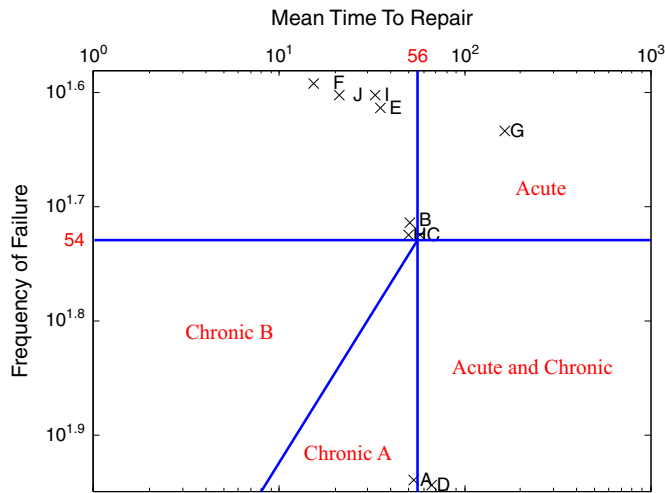
A falls in the chronic A region. A falls in the FTM region in the DMG (medium MTTR and high frequency of failure) which, upon comparison with its position in the JKD, is similarly classified. The OTF components of the DMG are E, F, I and J, which fall in the unclassified region in the JKD along with B and H, although they are very close to limit lines. Although H is classified as acute in the JKD, it too falls very close to the Limit$_{MTTR}$ border. Observation of the positions of B, C and H relative to the JKD axes reveals their locations mimic, the results shown in the DMG of medium frequency and medium downtime.

5. Discussion

This paper discusses two tools for allocating maintenance strategies while prioritising machine downtime according to two important downtime criteria: frequency and length of downtime. The DMG and the JKD allocate appropriate maintenance strategies depending on the location of the machines within the diagrams. To this point, the JKD has been used to prioritise machine downtime, whilst the DMG has been used to allocate maintenance strategies.

Within the DMG, each maintenance strategy can be the responsibility of a team in the maintenance department (function). For example, one team can be responsible for sustaining and auditing best practice for machines in the OTF region, with another team responsible for PM of machines in the FTM region. There can be teams for both RCM and CBM investigative approaches, a team for TPM and upgrading maintenance skills strategies, and a team for major overhauls and redesign projects of machines in the DOM quadrant. In short, the DMG model can be used as a framework for the allocation of machines to various maintenance teams and the performance monitoring of those machines by the respective teams.

Using the DMG as a comparative guide, the case studies show how the JKD allocates maintenance strategies. From the examples presented, it is not obvious which tool is pessimistic. In the cases where the JKD seems pessimistic, upon closer inspection of the location of the components relative to the axes of the JKD, we find their position is similar to that shown in the DMG. The difference is that the JKD contains four sections to allocate four maintenance strategies, whilst the DMG contains nine and can allocate five. In the JKD, there is no clear section to allocate FTM.

The JKD's advantage over the DMG lies in its scaled axes. The location of machines relative to limit lines is measurable. Therefore, if no maintenance action is taken, the user

(maintenance technician) has a good idea of which region the machine/failure code might fall into next. Although not obvious from the case studies presented, the JKD can be used in "trend plots" to monitor the movement of machine performance over several time periods. Although this is possible in the DMG, the DMG is almost "binary" in nature for each cell; either a machine falls in one of the sections of the grid or it does not. It is not obvious to see how far a machine is from the limits, unless a method such as fuzzy logic is incorporated, as reported in Labib *et al.* (1998b), Sudiarso and Labib (2002) and Yuniarto and Labib (2005). Another advantage of the JKD over the DMG is its mechanism to find the threshold limits.

6. Conclusion
To be competitive, maintenance organisations must provide timely delivery of quality products. Adopting the right maintenance policy is key to achieving this objective; it reduces costs by minimising downtime and leads to improved quality and productivity. A practical maintenance policy selection method is preferable, but the various maintenance strategies are incomparable. The findings of this paper suggest that the DMG and JKD are suitable tools to allocate appropriate maintenance strategies based on two downtime criteria: frequency and length of downtime.

It is clear from this study that both the DMG and JKD have pros and cons and, as such, there is no "winner". However, it is hoped that such work will encourage further research to integrate the methods, validate them, or develop more innovative approaches towards criticality analysis and the selection of appropriate maintenance strategies.

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