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Towards a Simpler Selection Process for Maintenance Strategies

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Abstract

Recent research at four large manufacturing sites in the North East of England showed that maintenance organisations were failing because they were locked in a cycle of *quick fix* and *mend* despite deploying extensive planned maintenance policies. Consequently they were unable to plan and formulate strategies because they did not have the time. Simple and quick tools were needed to select the best maintenance approach for the machines and the plant. Two possible selection tools were developed. Firstly a truth table was produced based on the key characteristics of each maintenance approach and these mapped against simplified failure mode combinations. This offered a quick and easy selection method for machines, based on failure mode patterns. Secondly, the macro level was addressed using a conceptual model employing a 2x2 matrix. This consisted of two axes, the level of machine failures and the level of improvement activity. The resulting framework was used to predict how maintenance organisations would progress from a state of reactive maintenance towards *world class*. Then informed by the truth table it was possible to select an appropriate maintenance approach which was most suitable for each stage. It is suggested that these two methods offer simple and quick approaches to guide vital maintenance decision making at plants in difficulty. This of course does not preclude the need to develop maintenance strategies but rather facilitates this process by freeing up time and resources.

Keywords: maintenance approaches, conceptual model, matrix, truth table

1. Introduction

Many manufacturing based maintenance organisations in the UK fail to reach the levels of advanced maintenance practice expected of them (Cholasuke et al., 2004)This is surprising because the body of knowledge and advice relating to maintenance management is copious e.g. (Marquez, 2007; Mobley, 2001; Nakajima, 1989; Pintelon & Gelders, 1992; Wilson, 2002; Wireman, 2004). In a review of maintenance organisations in the North East of England Mitchell et al. (2002) found that from a sample of 23 companies, 52 per cent had poor to fair levels of maintenance and only 16 per cent had adopted advanced maintenance strategies. A more recent benchmarking study by MacIntyre et al. (2005) yielded similar results. Clearly there is some inertia stopping maintenance organisations from developing beyond the basic levels of maintenance. The work by Robson (2010) went some way toward a solution by recommending a strategic way forward for practitioners to follow but it was also acknowledged that some companies still found it difficult to formulate strategies and plans because they were locked in a cycle of *quick fix* and *mend*. What was needed to unlock this cycle were quick and simple ways of selecting the right maintenance approach so that machine failures could be reduced.

One of the most difficult but important policy decisions maintenance professionals have to make is what maintenance approach to use and when? This choice arises on two occasions. Strategically, when a single maintenance approach is being adopted by a company e.g. Planned Maintenance (PM), Total Productive Maintenance (TPM) or Reliability-Centred Maintenance (RCM), or tactically, when a decision is being made on how an individual machine should be maintained and which maintenance approach is most appropriate e.g. Run to Breakdown (RTB), Preventative Maintenance (PM), Condition based Monitoring (CBM). The problem encountered at the case study sites investigated by Robson (2010)was that there was no simple process by which the busy maintenance professionals could logically and systematically make decisions without becoming embroiled in the relatively complex and time consuming methods such as Reliability Centred Maintenance or Failure Mode, Effect and Criticality Analysis (FMECA).This study proposes two basic methods to resolve these issues, a truth table and conceptual model employing a 2x2 matrix.

The succeeding sections of the study are arranged as follows: Section 2 presents observations from the empirical research; Section 3 provides a comprehensive review of maintenance approaches; Section 4 develops the truth table; Section 5 presents the conceptual model; Section 6 the conclusions.

2. Observations from Research and Motivation

Empirical research was carried out by Robson (2010) at four case study sites *to investigate the impact on manufacturing performance of the linkage between maintenance and manufacturing strategy*.The companies were kept anonymous by naming them according to industrial sector i.e. Foodco, Autoco, Steelco and Pharmco. From a methodology perspective, the research used a newly developed diagnostic tool (Robson, 2010) which was populated from rich data gathered from semi-structured interviews. The analysis defined the status at each plant which led to a series of strategic recommendations for practitioners to consider. However, reflecting on the difficulties that individual maintenance staff were experiencing on the ground it was incumbent on the researchers to further consider *short term* tactics which could free up time for the more strategic elements to proceed. Steelco and Foodco had acute problems because they had excessive levels of machine failure despite deploying large planned maintenance systems. It is not unusual for companies touse planned maintenance as the primary maintenance approach because it is recommended by most experts (Wireman, 1990 p.98) and often considered a pre-requisite to more *advanced* techniques (Shirose, 1992). However in the cases of Steelco and Foodco this corporate strategy was not working. A remark by a maintenance craftsman during plant interviews highlighted the frustration of frontline staff 'we need to be fixing the things that are breaking down first and worry about the machines that might, later'. This resounding statement of the obvious was difficult for junior staff to convey to senior managers because they felt locked into corporate systems and policies. Somehow senior leaders in manufacturing companies need to be convinced that maintenance approaches and tactics should be applied and adjusted according to the situation rather than the adoption of a *blanket* approach which often does not work! The next section begins the development of two new methods which will open the debate around this topic and this process begins by a review of the many maintenance approaches that are available for selection.

3. Review of Maintenance Approaches

3.1 Run to Breakdown (RTB)

Run To Breakdown (RTB) - also described as *Operate to Failure* (OTF) (Kelly, 1997) is simply a tactic where a machine is allowed to operate until it fails. This can be a valid strategy provided aspects of criticality, cost of failure, availability of spares, consequential damage are all taken into account. It should be noted that RTB is not about allowing machines to fail without prior thought or consideration.

3.2 Preventative Maintenance (PM)

Preventative Maintenance (PM) is the classical approach to maintenance. Originally termed *planned maintenance* or *scheduled maintenance*, it can be defined as the reduction of failures through inspection, servicing, lubrication and repair of equipment, at set frequencies'(Slack, Chambers, & Johnson, 2007) or according to (Kelly, 1997), 'the adjustment, calibration and repair actions, which are needed to correct or prevent failures'. This type of activity mainly occurs when the machine is out of service and for this reason such work must be well managed to be effective. The levels of PM intervention can vary from a simple visual external examination executed weekly, to a periodic overhaul or replacement in kind. Examination frequencies are somewhat subjective because they are often established from manufacturers' data or in-house experience and local knowledge. This can bring the technique into question because the cost effectiveness of this type of *fixed* time maintenance approach relies heavily on the predictability of the machines reliability and its time to failure (Kelly, 1997).

3.3 Computer Maintenance Management Systems (CMMS)

To facilitate the distribution of work, instructions are relayed to the craftsmen via work orders, examination sheets, job cards and instructional check-lists. These administrative tasks can be planned manually or more often processed via a Computer Maintenance Management System (CMMS). The latter is useful for automatically scheduling work and for storing feedback information such as the completion and status of work orders etc. An additional benefit of a CMMS over a manual system is that status and historical data can be readily accessed by maintenance and production personnel at convenient locations throughout the plant.

3.4 Condition Based Maintenance (CBM)

Condition Based Maintenance (CBM) is used to measure machine health over time. It triggers interventions only when the equipment and facilities require it (Slack et al., 2007). By doing so, this makes it possible for machine life to be maximised without incurring unplanned stoppages. A key advantage of CBM is that a timely intervention can prevent catastrophic failures which might cause damage to neighbouring parts and components. The downside of course of CBM is that the machine still needs to be out of service to carry out the repair work. The use of CBM is limited because a 'readily monitorable parameter of deterioration' (Kelly, 1997) is needed before the technique can be applied. CBM is generally deemed a more *proactive* approach than PM, because machine health can be monitored and measured whilst the machines are running. The most basic form of CBM, is an *uptime PM* where the craftsperson or operator uses *senses* to pick up any malfunction or machine deterioration e.g. unusual noises, smells, overheating or vibration. Often these issues cannot be *seen* when carrying out PM's in a shutdown situation. In practice manual monitoring can be a time consuming and laborious process and its success relies on the diligence of individuals. For critical applications, and in situations where machines are not accessible or condition not detectable by humans, technology has been developed to automate the process. There are several tools and techniques which come under this CBM umbrella some of which are discussed next.

3.4.1 Vibration Analysis

There are two main approaches used to carry out vibration analysis. One involves a fixed installation and the other the use of portable devices to take measurements at specific intervals and points around the machine. Historically, fixed systems tended to be installed on critical pieces of equipment where any variation from the norm needed to be immediately determined and enunciated. These would be used in critical applications e.g. turbines, alternators, ventilation fans etc. In this case *normal* vibration levels would be set when the equipment was new and any deviation above a certain level would be alarmed. In the case of portable monitoring equipment this uses the same technology but is more sophisticated in its outputs. This type of approach is usually employed periodically on selected key equipment. Here *inspectors* follow a set pattern or route taking readings at marked points on the machines. Vibration analysis technology works on the principle that machine vibrations can be detected using a sensor. The resulting spectrum of frequencies is then analysed using filtering methods coupled with the ability to relate the characteristics of the resulting spectra to the mechanics and components of the machine. From this analysis the machine health can be evaluated and any failing components identified.

3.4.2 Oil Debris Analysis

This is a technique used to measure the physical condition of a machine by means of analysing the state of its oil and the particles within it. The process consists of taking a sample of lubrication oil from a machine for analysis in a laboratory. This determines the number of particles, the type of material deposited and the particle sizes in the lubricant. From this data it is possible to establish the health of the machine by assessing the degradation and wear of the internal components. Through successive sampling it is possible to trend and predict the point of failure. Oil analysis is also useful to measure the condition of newly purchased equipment or and the impact to the machine following maintenance interventions. Due to time and cost this method is often restricted to key machinery. In a few special cases other tribology techniques, such as the inclusion of specialist additives can be used to increase the longevity of highly critical machines.

3.4.3 Thermography

Infrared thermography is a non-contact, non-destructive method for monitoring electrical, mechanical and structural systems. By use of a thermal imaging camera, temperature differences and gradients can be observed and recorded whilst the equipment is in service. The images are then used to inform remedial work. In many case equipment problems can be picked up with this approach which are difficult to detect any other way e.g. loose connections on electrical switchgear, cable overheating, damaged insulation on ovens, coolant failures etc.

3.4.4 Other Techniques

There are many more techniques which can be employed for CBM. Examples include methods of measuring deterioration of vessels and structures, crack detection and corrosion etc. (Kelly, 1997) but for the purpose of this review the main techniques have been covered in this section.

3.5 Total Productive Maintenance (TPM)

Total Productive Maintenance (TPM) (Nakajima, 1989) is one of a suite of Just in Time (JIT) techniques (Slack et al., 2007) which builds on the Total Quality Management (TQM) philosophy of *zero defects* (Crosby, 1980). Founded on the concept of the *five pillars* i.e. improve equipment effectiveness, autonomous maintenance, planned maintenance, train all staff, achieve early equipment management, TPM uses these guiding principles to steer maintenance effort. It fits seamlessly and is complementary to other JIT techniques and therefore encourages the use of cross-functional teams to work on the reduction of the *six big losses* i.e. breakdowns, set-ups, idling and minor stops, reduced speed, start-up and quality defects so that Overall Equipment Effectiveness (OEE) can be improved (Shirose, 1992).TPM also uses *5S* techniques. This involves the removal of non-essential equipment, ensuring equipment and tools are *ordered* and machines are *cleaned* and *inspected*. The idea suggests that by following this approach all defects will be found and rectified. The final stages involve sustainability and prevention and this is achieved through the establishment of *standard* operating/ maintenance procedures, which ensure basic maintenance and lubrication is carried out.

Japanese manufacturing companies have used TPM for many years and with great success but some UK initiatives have faulted. The example at Toyota (Ohno, 1988) and the research of (Hanson, 1995) demonstrate that many Japanese companies reach very high levels of reliability in respect to their machines and processes. On the other hand, implementation of TPM in the UK has proved problematic. The main reason cited by authors for poor progress was *cultural* reasons. For example, empirical research by (Bamber, Sharp, & Hides, 1999; Cooke, 2000) showed that several companies were experiencing resistance to the introduction of TPM and there were many barriers to successful implementation.

3.6 Reliability-Centred Maintenance (RCM)

Reliability- Centred Maintenance (RCM) is a methodology used to identify the most appropriate maintenance for a machine and has proved very successful in the aircraft industry (Moubray, 1992). However it is time consuming and involved. The analytical process asks seven fundamental questions about the asset or process being reviewed:

1. What are the functions and associated performance standards of the asset in its present operating context?
2. In what ways does it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable proactive task cannot be found?

Source: RCM 2 – Reliability- Centred Maintenance (Moubray, 1992)

Essentially, the *function* of the machine is established first which includes defining its purpose and what it was originally designed to do. This establishes the performance levels expected by the users and from this potential failure states or *functional failures* can be identified. Building on this basic information the potential *failure modes* and *failure effects* are determined. These are then organised into four *failure consequence* groups; hidden, safety & environmental, operational and non-operational and these potential consequences evaluated to define the maintenance strategy for a given machine and to arrive at the most appropriate tactic. Typically RCM interventions are resource intensive and team members need training or/and external support.

3.7 Root Cause Analysis (RCA)

Root Cause Analysis (RCA) is a technique normally applied to safety investigations and risk assessment. This is a systematic approach often supported with software packages and proprietary methodologies e.g. Taproot (Paradies & Unger, 2000). RCA is a logical process of problem solving to determine the *root cause* of a failure or breakdown. One definition of the term *root cause* is 'the most basic cause (or causes) that can be reasonably identified, that management has control to fix and when fixed, will prevent (or significantly reduce the likelihood of) the problem's reoccurrence' (Paradies & Unger, 2000).

3.8 Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a problem solving process which is one of the stages in the RCM process. Normally it is recommended that this work is carried out by cross functional teams which have all appropriate disciplines represented. The purpose is to identify all of the ways that a process, product or machine can fail (Mcdermott, Mikulak, & Beauregard, 1996). It is similar to a safety risk assessment where severity, probability and frequency of exposure are the factors considered (Bahr, 1994) but in the case of FMEA the 'frequency of a failure being detected' is used (Mcdermott et al., 1996). Other variants exist, such as Failure Mode, Effect and Criticality Analysis (FMECA).This involves a fourth element which considers the machines criticality to the process or business. A summary of the maintenance approaches and their characteristics are provided in Table 1. This information is used in Section 4 to develop a truth table which aids the selection of maintenance approaches for a machine.

Table 1. Maintenance approaches: their philosophies, advantages and disadvantages

Technique	Philosophy	Advantages	Disadvantages
RTB (Run to Breakdown)	Equipment of low priority, low consequential loss, easily repaired are allowed to fail.	Simple, no up-front effort needed apart from the assessment of criticality and cost and speed of repair.	Failures occur randomly
PM (Preventative Maintenance)	Equipment is regularly maintained at fixed intervals the failure modes are known and can be observed.	Simple, cheap in terms of training , craftsman normally already have the skills	Equipment needs to be out of service. Difficulty in determining the *right* frequency: too early and effort is wasted , too late and failure is likely
TPM (Total Productive Maintenance)	Zero defect philosophy. Eliminate the small defects and the large defects are less likely to occur.	Should bring production and maintenance together. Simple approach which makes common sense. Clean machines and standards for operating and maintaining. Part of JIT.	Time consuming and initially can have little return for a lot of effort. Cross functional difficulties might occur if not managed as operators take on traditional maintenance tasks.
CBM (condition Based Maintenance)	Monitor machine health so that interventions can be planned at the appropriate time, averting machine failure.	Monitoring takes place whilst the machines are running. Catastrophic and consequential damage is minimised	Fixed installations can be expensive especially if remote monitoring is needed. Either in house technicians need to be highly trained or need external support.
RCA (Root Cause Analysis)	If equipment fails then find the primary reason or reasons and eliminate so that there is not a reoccurrence.	Maintenance resource effort is targeted on machines that have actually failed. If applied appropriately can significantly reduce overall breakdowns by eliminating repetitive failures.	Reactive approach, machines have already failed at least once. Dedicated resources are needed so that they are not disturbed in their problem solving and improvement efforts. RCA, facilitation skills needed.
FMEA (Failure Mode and Effect Analysis)	Identify the possible failure modes of a machine or system, their effect and consequences if they fail, also, how critical in terms of agreed criteria would such a failure be?	Pro-active approach which can be carried out whilst the machine or system is are running	Time consuming and somewhat open ended, therefore must be focused and have a clear set of priorities. Resources need to be specially trained and competent in the technique. Not as involved as RCM.
RCM (Reliability-centred Maintenance)	Similar to FMECA but more focused on reliability and the probability of failure	Highly successful in the aviation industry	Time consuming and somewhat open ended, therefore must be focused and have a clear set of priorities. Highly analytical, resources need to be specially trained and competent in the technique.

4. Development of Truth Table

Arising from the review in section 3 it was noted that there were two existing techniques (RCM and FMECA) which could be specifically used to select maintenance approaches but both require a 'substantial commitment of resources'(Moubray, 1992 p.283). Moreover maintenance staff are likely to require training or support from external people to provide guidance through the fairly complex and detailed analysis. For the busy maintenance organisations reviewed in Section 2 there were clearly not enough resources and time to spend on such time consuming techniques. Having said this RCM and FEMECA techniques have been tried and tested in the aviation industry for many years and therefore are a reliable starting point for any new approach. After due consideration of the parameters underlying these methods opportunities to develop quicker and simpler approaches were evaluated. For example it was found possible to reduce the scope of the questioning by considering *only machines and processes that had actually failed* rather than *all machines that might fail*. Secondly, it was possible to consider decisions *objectively* e.g. Yes or No conditions rather than *subjectively* e.g. likelihood of failure. However, to develop these ideas further it was necessary to analyse and review Table 1 in more detail.

If the differences and similarities of the maintenance approaches covered in Table 1 are considered, a number of important observations and comparisons can be made. Firstly, it can be noted that PM and TPM relies mainly on *inspections* or *replacements* carried out by craftsmen and operatives and therefore covers *known* types of failure which can be *seen* e.g. leakages, loose parts, wear and tear, missing or incorrect components etc. Whereas, in the case of RCM and FMECA, these selection techniques are based around a comprehensive analysis of how a machine or system *might* fail. In this technique all possible failure modes would be considered having due regard to criticality. These approaches cover failures which can be *seen* or *hidden* but also need to be *known*. On the other hand CBM deals with *known* failure modes but unlike PM and TPM measure the condition and deterioration of machines which are often hidden from the naked eye. Finally, RCA is a purely reactive technique which can be used after a failure had occurred. Its primary goal is to prevent failures from happening. The root cause is determined using a trail of evidence and a structured problem solving approach (Paradies & Unger, 2000). However, in the case of RCA the failure mode is *unknown* but can be *visible* or *hidden*. So summarising a number of binary states were noted. Firstly, some approaches relied on failures to occur, others did not. Some approaches required faults to be observed and others were able to detect faults that were invisible to the naked eye. Moreover some failures were known and others were unknown. Taking all of these observations into consideration it was possible to create the truth table which is presented in Table 2. This truth table provides an overview of all possible combinations for the given parameters and facilitates selection of the most appropriate maintenance approach for each scenario.

Table 2. A truth table which matches maintenance approaches to four key factors

Scenario	Critical	Failure Mode Known?	Failure is seen?	Machine failed?	Maintenance approach?
1	YES	NO	NO	NO	NONE
2	YES	NO	NO	YES	RCA
3	YES	NO	YES	NO	PM,TPM
4	YES	NO	YES	YES	RCA
5	YES	YES	NO	NO	CBM
6	YES	YES	NO	YES	RCA,CBM
7	YES	YES	YES	NO	PM,TPM
8	YES	YES	YES	YES	RCA,PM.TPM
9	NO	NO	NO	NO	RTB
10	NO	NO	NO	YES	RTB
11	NO	NO	YES	NO	RTB
12	NO	NO	YES	YES	RTB
13	NO	YES	NO	NO	RTB
14	NO	YES	NO	YES	RTB
15	NO	YES	YES	NO	RTB
16	NO	YES	YES	YES	RTB

4.1 Analysis of Truth Table

If the truth table in Table 2 is considered in detail some interesting observations can be made. Firstly, there was no single technique which covered all possible scenarios. Secondly, scenario one offered a hypothetical state where no suitable maintenance approach was suitable. This suggested that there were dormant or potential failures that cannot be predicted. Thirdly, Root Cause Analysis (RCA) was found to be suitable in 50 per cent of the cases and could be used in all situations where the machine had already failed. Moreover, PM and TPM were not universal techniques as they only covered a third of the possible critical scenarios. This was because they were dependent on *knowing* the failure mode and *seeing* it. Obviously RTB was suitable when machines were non critical. Finally RCM and FEMECA were not considered in the table because they are purely selection techniques but clearly can be used at any time. Table 2 should be interpreted with caution however because it does not take into account how frequent a combination of failure modes occur. For example RCA might represent 50 per cent of the possible scenarios but this does not mean that they all occur in equal amounts. It might be that the combinations favouring a selection of PM may be frequent because most failures are *known* and *seen*.

If the philosophy of *only focussing on machines that have failed* is adopted this further simplifies the decision making in Table 2 because only scenarios 2,4,6 and 8 become relevant. Scenarios 1,3,5,7 are discounted because they *have not failed* and scenarios 9 to 16 are non-critical items which would be automatically filtered out because downtime data typically only relates to critical items i.e. machines or processes that have already failed and stopped production. Using this logic the maintenance approach of choice under *quick fix* and *mend* conditions is Root Cause Analysis.This truth table provides a simplified method of choosing the most appropriate maintenance approach for a machine but does not address the most appropriate approach for a manufacturing plant and in what situation it should be applied. This topic is expolored in the next section.

5. Development of 2x2 Matrix

According to MacIntyre et al. (2005); Mitchell et al. (2002) maintenance organisations and their progress can be measured by the levels of *best practice* they are deploying at any given time. This acknowledges that different companies can be at different stages of development along a continuum towards *world class* (Wireman, 1990). However, although the work of (MacIntyre et al., 2005) generated a diagram mapping this progression, a more detailed model was needed to explain how companies might transition between each stage. To do this a simple 2x2 matrix was developed. Work by Cholasuke et al. (2004 p.10) had shown that there was a strong correlation between the level of continuous improvement and machine failures so these two dimensions were used to form a grid. This comprised of a vertical axis showing “High” and “Low” level of improvement activity and a horizontal axis indicating “High” and “Low” level of machine failure. The resulting matrix is shown in Figure 1.

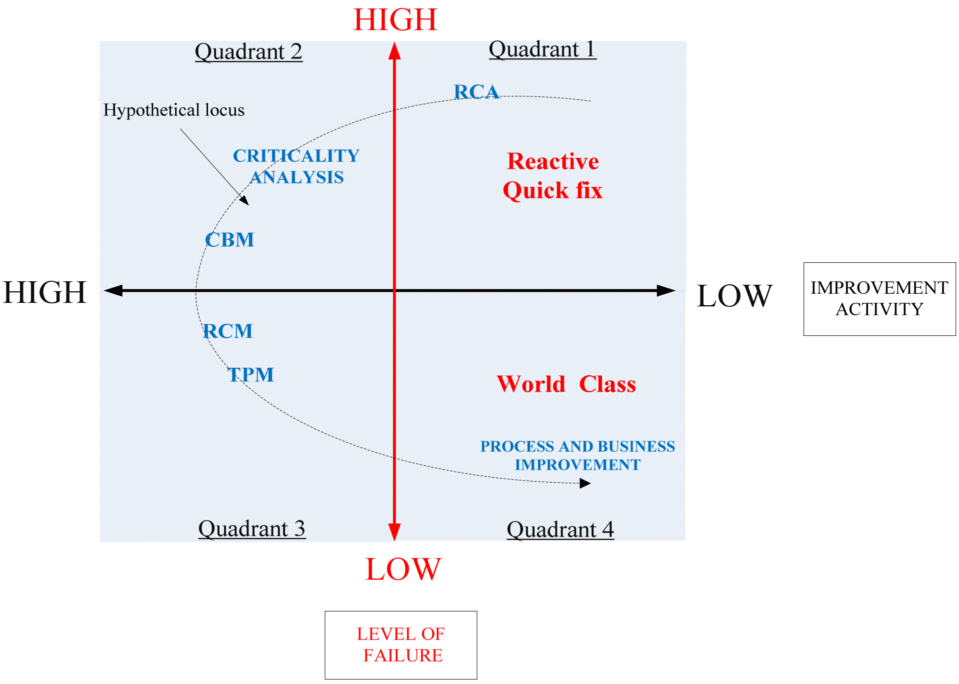

Figure 1. A conceptual model to determine best maintenance approach for plants

5.1 Interpretation of the Model

Using this grid it is possible to map the position of a manufacturing plant into one of four quadrants based on the level of failures and level of improvement activity taking place. From this it is possible to predict a hypothetical locus which shows how a company might progress from a *reactive* to a *world class* state. At the same time it was possible to logically advise the most suitable maintenance approach in any given quadrant. It can be seen from Figure1 that *quadrant one* is the state of *high* machine failure and *low* improvement activity and aligns to the status of the four case study companies discussed in section 2. The previous section determined that the most effective maintenance approach in this situation was Root Cause Analysis. According to Cholasuke et al. (2004) when improvement activity is increased machine failures will fall. It therefore follows that to move from *quadrant one* to *quadrant two* an increased amount of improvement activity is required. As root cause analysis reaps dividends repetitive failures will reduce and there will be a greater availability of human resources because less time is being spent on breakdowns This means as companies move into *quadrant two*, more advanced techniques can be adopted to optimise and improve the planned maintenance system, such as criticality analysis and condition based maintenance. As machine failures continue to diminish it is envisaged as companies move to *quadrant three* they can take on even more advanced techniques such as RCM and TPM. Eventually when *quadrant four* is reached comprehensive and reliable systems are in place and there is little time expended on breakdowns. At this point there is stable platform where all work is planned and predictable so maintenance staff can be released to work on the process and wider business related improvements. This model provides a conceptual framework form which practitioners can position their manufacturing plant and from this assess the most suitable maintenance approach based on status.

6. Conclusions

This paper has provided a starting point for an important debate around the selection of maintenance approaches and the situations where they might or might not be appropriate. Without this information maintenance managers will continue to be influenced by *external experts* and have arbitrary maintenance approaches imposed on them from senior leaders. The profile and credibility of maintenance needs to be raised within manufacturing organisations and to this end, maintenance managers have to be able to put forward strategic plans and arguments which stand up to scrutiny. Without the appropriate methodologies supported by research evidence, maintenance will continue to be the *poor relation* or *Cinderella* department (Mitchell et al., 2002) which is driven by others.

The key driver for the new and simplified selection methods was the lack of available maintenance staff to carry out significant and continuous levels of improvement work. If sufficient numbers of *surplus* staff were available then it would be possible to use a two pronged approach where reactive and proactive work could happen in parallel. However, although this would speed up the path to *world class* it is arguable whether this would change the sequence of maintenance approaches adopted. Having extra staff is an unlikely scenario because in all case studies investigated by the authors the emphasis of the companies was on reducing cost and headcount rather than adding people.

In this paper a number of arguments were presented. First of all that strategies need to be appropriate for a given situation. This contradicts the *one size fits all* policy used by many companies. Secondly, when the failure modes are *hidden* or *unknown*, stalwart approaches such as PM and TPM are no longer valid. In these cases, more analytical techniques are needed to solve the more complex problems. Thirdly, if equipment continues to fail for the same reason, then clearly the maintenance approach is not working. Given these conditions it makes more sense to consider alternative approaches which are more effective.

The adoption of different maintenance approaches according to the level of machine failure and level of improvement activity will drive a change in skills and culture over time. It was clear from the analysis that when maintenance organisations start to improve the techniques that can be applied become more advanced and complex. As machine failures diminish there will be a need for a dramatic change in the type of skills maintenance people need to develop. Instead of rewarding the best *fixers* and *fire-fighters* companies will need to encourage *facilitators* and *analysts*. This will be a significant cultural and organisational change that will have to be managed very carefully.

The topics discussed in this paper were focussed on companies who found themselves in quadrant one and in need of quick and simple advice to begin the long process of improvement towards *world class*. It should be emphasized that the two guides presented in this paper are “additional to” and do not “replace” a documented maintenance strategy which is essential to steer organizations as they move forward.

The authors’ recognise that further work is needed to test the concepts and propositions which were set out in this paper and are continuing to work with manufacturing organisations in the North East of England as well as further afield to gather more data which can be used to further the research.

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