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A repairable mechanical system reliability assessment methodology applied in a steelmaking context.

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Abstract

An analysis method for reliability assessment of repairable mechanical systems is presented in the context of the Hot Strip Mill section of a large steelworks. The reliability analysis process is defined and operated using a three level modelling procedure, each of which functions within a different time base, thus enabling the timely identification of potential deviations in reliability performance. The main modelling approach deployed is based upon the Power Law Process, which is embedded within an automated analysis tool. The efficacy of each of the deployed modelling process is determined by the application of appropriate statistical tests. The results from this process are used to enable an in depth analysis of why the reliability performance of the system under review has changed. A practical application is presented with reference to two strip coilers that operate within the Hot Strip Mill. The approach is however generic and would be applicable to any large scale mechanical repairable system.

Keywords: Hot strip mill, repairable mechanical system, Power Law Process analysis.

1. INTRODUCTION

The need for more efficient manufacturing systems has resulted in greater emphasis being placed on the quality of the processes. This has produced a realisation of the need for higher levels of plant availability and better maintained machinery and managed processes. Meeting these requirements places great emphasis on the accurate and timely assessment of the reliability of such plant. Many of these systems are complex repairable systems operating in difficult conditions and exhibiting various modes of failure and performance deterioration [1]. In this context a repairable system is defined as “a system that, when a failure occurs can be restored to an operating condition by some repair process other than replacement of the entire system” [2]. This definition is applicable to the entire steelworks plant in which this research was undertaken and to its subsystems, which are predominantly mechanical with electrical or hydraulic drives and electronic control which are installed in areas such as the Hot Strip Mill considered in this paper. The diversity in the operating conditions and consequently the failure modes arising in this plant is such that the assessment of reliability can only realistically be based upon analysis by multiple statistical models. This paper considers some basic approaches to reliability modelling with an emphasis on its use as a process management tool.

Reliability monitoring is practised throughout industry, often through its association with process availability. However the greater in-depth analysis needed to consider the reliability of what are often large and complicated repairable systems remains a relatively unexplored area. When deployed such approaches usually rely upon the provision of specialised knowledge for their efficient use. This paper presents an approach that uses easily understood reliability engineering tools that can be embedded within a process management system for continuous utilisation by non-experts. There are few if any readily identifiable examples of the continuous application of reliability modelling techniques to large scale repairable systems within the steel making sector and as such this research is considered to be timely. In this case the approach is developed to support the operation of the Hot Strip Mill with consideration of a pair of strip coilers which operate within it.

The aim of this work is to construct a modelling technique which can continuously analyse and monitor the reliability status of multiple process systems. It has been previously identified that attaining robust data relating to past reliability performance can be problematic in part due to the tendency for the discarding of accumulated data. One of the problems is data availability; since most systems were custom built access to the legacy of data they contain can be limited. This situation is becoming less troublesome with the move towards application independent databases equipped with embedded procedures which support data acquisition and standardisation.

Repairable systems may be large and complex and often consist of a number of subsystems each with their own reliability characteristics. This presents a challenge when assessing the reliability and performance of the overall system and many different analysis models have been developed to cover all types of such systems. Their application requires knowledge of statistical methods; often an iterative approach is required to identify the most suitable model. These iterative processes can be difficult and time consuming and require considerable expertise. Once a model is established it is possible that factors such as changes to the operating environment mean that reliability characteristics of the systems and hence the applicability of the applied model can change. Such events need to be flagged up for further analysis and model development, as is the case with the deployed system used in this example.

The reliability analysis method (RAM) outlined here in is predominantly automated and is facilitated by applying the Power Law Process (PLP) reliability analysis model [3]. The challenges and limitations of applying the PLP for the analysis of several similar repairable systems has been recently considered [4] and the need for more research across a wider industry base was identified. The provision of such support is the basis of the following work in which steelworks operational data is used to demonstrate that changes and trends in system reliability status can be easily identified.

2. THE STEELWORKS PLANT

The steelworks occupies a site which covers over twenty square kilometres and contains assets valued at several billion pounds. The plant is split into four manufacturing sections which form a sequential operation. These sections are predominantly stand alone and are considered as separate business units. They are the “Heavy End” where the main focus is primarily iron making. The next section is the “Steelmaking” which processes the primary iron through electric arc furnaces and supporting thermal process vessels with the output being cast slabs. These are passed into the third section, “Hot Strip Finishing” which forms the cast slab into rolled coils through the Hot Strip Mill. This process accounts for the major deformation within the steel. This is the section within which the research described in this paper was conducted and it is depicted in Figure 1. The coils produced can have two further routes, either straight to the customer or for final working in the “Cold Strip Finishing” section.

INSERT Figure 1 Hot Strip Mill Production Process.

The steelworks encompasses the latest steelmaking methodologies using a mixture of plant. Some sections are largely unchanged since the site’s inception. Some sections have been modified or indeed have been installed as new processes have been introduced. Each of the four manufacturing sections contains multiple operating processes with constituent machines being replaced as and when necessary. The result is that some operating systems can contain machines and operating units with a mix of ages ranging from as new condition to several decades old. This means that it is almost impossible to calculate the actual operating age of any system and correspondingly that any system installed is expected by default, to last several decades as a minimum.

3. RELIABILITY ANALYSIS OF REPAIRABLE SYSTEMS

Before presenting a brief review of the reliability analysis of repairable systems it is useful to define two important terms. In this context a trend can be defined as “a steady increase or decrease over time in a reliability quantity of interest” and a pattern is taken to mean “any deviation from a stable state or condition resulting from some assignable cause” [5]. Both terms are used in the following sections.

Two of the most common models for the analysis of repairable system failure processes are the renewal process (RP) and the non-homogeneous Poisson process (NHPP). The RP considers that following a perfect repair the system is returned to “as good as new” condition. In practice in repairable mechanical systems most standard maintenance reduces the failure intensity but does not leave the system “as good as new”; hence the result is an imperfect or minimal repair [6]. The NHPP assumes that the system is subject to minimal repair and is returned to the same state as it was before repair. There is a significant volume of research related to the selection of appropriate modelling and analysis methods. This has been well considered in a review by Lindqvist [1] who follows the evolution of imperfect repair models proposed by Kijima [7] from an initial definition by Brown [8] to the method he develops in his own work. Other research in this area includes that reported by Krivtsov [9] who considered how to expand the NHPP analysis methods from the usual Weibull Power Law distributions to incorporate other life data analysis methods.

It has been suggested that the homogeneous Poisson process HPP and NHPP are actually specific cases of the generalised renewal process and can be used in repairable system applications [10]. Crow [11] has also addressed the problem of imperfect repair in the general renewal process analysis method. He proposes two ways of calculating the “virtual age” of the system; the first assuming that the last repair is returned to full operating status and the second that all previous repairs are returned to full operating status. The problem of distinguishing between the extremes represented by the RP and NHPP has been further investigated [12] with resolution suggested using the trend renewal process (TRP), of which the RP and NHPP are identified as special cases [13].

In many repairable systems one of the main aims is to detect trends in failure data which occur over time. Methods used for testing these trends include graphical and statistical approaches [13]. These approaches include the methods deployed in this research, which are considered as they are applied in section 4. These trends may be monotonic indicating an improving or deteriorating system, or a non-monotonic such as a bathtub curve or a cyclic trend. Testing the statistical significance of apparent trends in failure intensities and hazard rates offers the potential for assessing the effect of ageing or learning in the operation and maintenance of industrial facilities [14]. Another class of models based on the trend renewal processes can be used to accelerate the internal time of the renewal process to represent cumulative wear [12].

Having briefly reviewed the most commonly deployed analysis method it has been shown that with appropriate care the NHPP family can support repairable systems analysis. The decision was therefore taken to build a reliability analysis method based upon the PLP. This is a special case of the NHPP that is widely used for the analysis of repairable systems within the reliability community. It was seen as a practical choice for the steel manufacturing environment. The PLP is the most popular process model which was introduced in 1974 and has formed a major part of this field with incorporation into military handbooks and other reference materials [3]. It is easy to use and understand and lends itself to many practical applications [15, 16]. The PLP analysis technique is widely used for the analysis of repairable systems due to its ability to analyse systems which are improving or deteriorating [6, 17]. It has been applied in the context of repairable systems that are not returned to "as good as new" condition after the replacement of a single component [18].

To demonstrate the suitability of this choice it is possible to consider next the manner in which PLP based approaches have been applied to the reliability analysis and performance assessment of repairable mechanical systems. A review of the reliability of repairable mechanical systems identified a limited number of practical examples. They include work by Weckman et.al using the PLP in an approach to modelling jet engine life [19]. This work suggested that the model's accuracy depended upon the engine's maintenance scheme which included the mandatory removals of the engine based upon elapsed time and use rather than deterioration. The paper highlights the difficulties of identifying the true failure parameters of any system and the relationship between the calculated reliability measures and deployed maintenance strategies, operating policies and other associated factors.

The reliability of service water pumps in a nuclear plant was considered in an investigation using the rate of change of pump failure [20]. The approach deployed two variants of the NHPP models, the log linear and the PLP, as comparative methodologies. The conclusion presented suggested that the developed approach could adequately map the variations in failure rates occurring due to periodic testing and maintenance activities and it was suggested that it may be used to survey ageing mechanisms and to assess the effectiveness of maintenance actions.

The use of a NHPP model for analysing the reliability of an overhead contact line in a railway system has been reported [21]. It was assumed that the system operated with "negligible" repair time and was subject to an imperfect repair scenario; the overall degradation of the system continues despite the replacement or repair of its constituent parts. The paper was mainly concerned with the deployment of an appropriate "goodness of fit" test and provided a detailed example of how and why such a tool may be deployed. This consideration needs to be applied to all such activities if the results of the modelling are to be effectively utilised; it is applied in this way in section 5 of this paper.

A method applying NHPP models to failure data obtained from a major car manufacturer has been reported [22]. This demonstrated the use of trend testing and considered methods of estimating the intensity function using the application of goodness of fit tests. The paper concluded that the NHPP model was appropriate for this data. The application of the PLP was also applied to assess the reliability of gearboxes and generators operating within onshore wind turbines [23]. The approach was found to indicate lower levels of performance than anticipated. The work also established a framework for the subsequent acquisition and utilisation of failure performance data.

Consideration of this and related research confirmed the conclusion that the PLP approach is suited to the application being considered. This was further confirmed with a concurrent review of the specialist software indicating that the PLP is the main analysis method used for repairable systems.

4 RELIABILITY ANALYSIS MODEL

This research was performed to identify and develop a methodology suitable for repairable systems installed in a challenging manufacturing environment. This research has led to the development of the RAM method described in this paper. Whilst not using unique reliability analysis methods this is presented as a novel approach to formatting standard reliability analysis models to analyse and monitor repairable systems deployed in a long term manufacturing scenario. This is a "common sense" approach to improving the condition of manufacturing assets (machinery) through long term monitoring and analysis. The concept adopted in this work was that the deployed approach would be used by plant operatives, who will be responsible for a range of technical and maintenance functions. These engineers will posses expertise in their relative areas but may have limited knowledge of reliability analysis.

It was thus important that the analysis method should be simple to operate and require minimal training. The analysis of previous research and testing indicated a need for a methodology capable of accurately tracking and monitoring plant reliability, as indicated by factors such as the time between failures of the multiple systems which will be operating simultaneously.

The developed approach which utilised analysis of the acquired data on three levels is shown in Figure 2. The proposed custom built analysis model combines three separate analysis methods, each of which is based on current reliability analysis techniques, with modifications where necessary. These methods and their application to the case shown in Figure 2 are outlined in sections 4.1, 4.2 and 4.3 of this paper.

INSERT Figure 2. RAM Method 1,2 and 3 indicators

The three reliability analysis methods have been constructed using standard uniform reliability analysis methods and time increments in order to maintain compatibility between analyses carried out in any operating area; however the system was constructed to apply the three models in combination with additional statistical analysis methods. The basis of this approach is to first deploy the reliability analysis method to model the systems reliability performance, This provides the capability of calculating the time between failures of all systems at a chosen point in time and the development of a monitoring function which plots the individual and combined reliability measures, whether positive or negative, relative to specified time increments. In providing these features it was intended that the system would be capable of performing a “comparative analysis” for areas of plant over time and between sections of the plant which are operated predominantly under the same conditions.

A goodness of fit statistical test is then applied to each systems failure data set to identify if the RAM method is suitable for the application. If the goodness of fit test does not give an affirmative result it is possible to split the failure data set into subsets and, by applying further iterations of the test to these subsets, to allow the identification of the portion of the failure data that could be influencing the overall goodness of fit test result. In effect this method can thus provide a means of allowing for the analysis of the cause of the non-applicability of the PLP and the associated change in reliability performance. Further details on this methodology are supplied in section 4.1 and section 5.3.

The deployed approach, shown in Figure 2, will monitor the effect of any changes that could occur following the replacement of a part, element or subsystem of a section of the plant. It will also monitor and help the identification of the causes of significant differences between items of similar plant in different location but under the same operating regime.

Overall the integration of the monitoring of individual sections of plant would thus contribute to knowledge regarding asset management across the entire plant. The operation of each analysis method and the applied goodness of fit tests and trend testing facilities deployed will now be considered in the following sections.

4.1 *Method 1: Instantaneous Mean Time Between Failures (IMTBF)*

Method 1 is the main reliability analysis method which uses PLP to model current reliability and to support a predictive mechanism. The accepted measure Instantaneous Mean Time Between Failures (IMTBF) is used to analyse complete data sets, from a selected starting point to the current date. It is deployed here to characterise the long term trend in time between failures, using the Power Law Process analysis method and is depicted in Figure 2a.

Analysis of system performance is normally undertaken with reference to the IMTBF. This method is a special case of the NHPP that uses a failure intensity function which is given by:

$$\mu(t) = \lambda\beta t^{\beta-1} \qquad (1)$$

The estimate of the failure rate $\hat{\lambda}$ can be made:

$$\hat{\lambda} = \frac{N}{T^{\hat{\beta}}} \qquad (2)$$

and for the process shape factor $\hat{\beta}$ from:

$$\hat{\beta} = \frac{N}{\sum_{j=1}^{N} Ln\left[\frac{T}{X_j}\right]} \qquad (3)$$

Where: X_j is the age of system at j^{th} failure, T is the system operating time and N is the number of failures within this time span.

The Instantaneous Mean Time Between Failures can be evaluated from:

$$IMTBF = \frac{1}{\mu(t)} \qquad (4)$$

The Method 1 operating algorithm was constructed to apply Equations 1 to 4 to establish IMTBF, which is used to identify the overall top-level reliability trends for the plant, area or system under consideration; it forms the long-term reliability monitoring method. This is intended to identify the plant level system reliability trends which indicate whether the area under review is undergoing overall reliability growth or deterioration. Experience indicates that data sets accessed by this analysis method may at times not be deemed to be behaving as defined by the PLP. This feature casts doubt on the efficacy of this type of analysis when used as a stand-alone tool and indeed is one reason for their limited application. This is an unavoidable and expected risk when accessing large data sets over a significant timescale with the type of range of operating parameters and outside influences seen by these manufacturing systems.

This feature was detected in this work by deploying an embedded the Cramer von Mises (CvM) “goodness of fit test” which has been proven to be suitable for use with the PLP method [22&24]. The Analysis system supports the further application of this method by allowing a goodness of fit test to be carried on the data to determine if the PLP can be correctly applied to the system over the period under review; in this case the analysis operated continuously from week “0” to the current date. Loss of “fit” clearly indicates some change in reliability performance and thus will help to identify discrepancies in the data which indicate the occurrence and location of special causes (if any) which could have affected the system.

To further confirm the statistical significance of the examined systems the Military Handbook Test, which has been identified as being suitable for trend testing with a PLP [3&25], is also incorporated into the RAM methodology. This provides a further check on the veracity of the IMTBF analyses by either correlating or disputing the calculated result. This comparison allows the identification of any trends in the system’s performance. These trends may be associated with changes in the operating environment or maintenance practices. Approaches enabling such considerations have been previously reported. These include the use of a generalized non-stationary NHPP model for scheduling preventative maintenance [26]. The need to identify the occurrence of behaviour changes has also been considered with the deployment of a segmented point process model [27]. The application and benefits arising from the approach deployed in Method 1 of this paper is considered in section 5.

4.2. *Method 2: Incremental Mean Time Between Failures (IncMTBF)*

Method 2 was developed using the application of PLP analysis applied over four week operating periods, with data being added incrementally. The results are presented in terms of a new performance measure created by the authors; Incremental Mean Time Between

Failures (IncMTBF). This is used to track the medium term time between failures and identify medium term trends in the system's operation.

This was derived from the RAM analysis methodology established in Method 1. It is calculated in hours using algorithms that are again based on Equations 1 to 3. For consistency the same starting date is adopted as for Method 1. Although this method uses the same calculation algorithm as Method 1 it is applied very differently. The intention is that for any required period an overall IMTBF can be broken down into incremental assessments of IncMTBF to demonstrate when significant events occurred. The systems breakdowns can be analysed from time zero (0) incrementally for each four week (672 hour) operating period. The analysis process continues by incrementally adding data acquired for each four week period to the existing data set until the required week number (normally the current, or a selected date) is reached.

This forms the main analysis tool of this whole approach. If an engineer wishes to consider the effect of the performance of the system during any given week period they can do so by comparing the IncMTBF value for the period up to and subsequent to the week in question. The basis of Method 2 is that the addition of data for any particular week that results in the PLP method being shown to be no longer appropriate can be identified and further analysis as to the cause of this behaviour enabled.

The IncMTBF was developed using the same equations as the PLP but with some modifications to represent the different application method. The Failure intensity function is given by

$$\mu_{inc}(t) = \lambda_i \beta_i t^{\beta_i - 1} \qquad (5)$$

The estimate of the failure rate $\hat{\lambda}_i$ can be made:

$$\hat{\lambda}_i = \frac{N_i}{T_i^{\hat{\beta}_i}} \qquad (6)$$

and for the process shape factor $\hat{\beta}_i$ from:

$$\hat{\beta}_i = \frac{N_i}{\sum_{i=1}^{N} Ln\left[\frac{T_i}{X_i}\right]} \qquad (7)$$

Where: X_i is the age of the system, N_i is the number of failures and T_i the time span at the i^{th} failure. The Incremental Mean Time Between Failures can be evaluated from:

$$IncMTBF = \frac{1}{\mu_{inc}(t)} \quad (8)$$

The method operates by calculating the IncMTBF values from the start of data collation up to the system operating time (*T*). It is calculated at 672 hourly increments (T_i = 672, 1344, 2016 to *T*) thereby allowing engineers to compare the differences in reliability performance arising between each 672 hourly operating period. This reliability tracking method was intended to be beneficial to engineers located in specific areas of the plant by allowing them to visualise and identify the reliability trends of the area under their control. The response speed of this analysis method to disturbances in established behaviour is a considerably shorter term than can be provided by the application of Method 1; this is a useful function in the timely identification of trends and failure patterns.

The application of this approach can be illustrated by the deviation in the calculated reliability values seeming to arise around Week 40 in Figure 2b. Applying this method the IncMTBF can be calculated from week 0 up to and including week 36 (giving a value of 97 hours) and compared to the IncMTBF resulting from the analysis of the week 0 to week 40 data (giving a value of 83 hours), which indicates a drop in the system's reliability indices. Continuing the analysis for one further increment, using week 0 to week 44 (giving a value of 103 hours) it would seem that performance has been re-established, if not improved. The critical point to be considered here is whether this behaviour relates to an actual deviation in performance or to some random fluctuation. The answer to the question may be found by considering the statistical significance of the PLP model being applied to this data at both this (Method 2) and the higher (Method 1) level. This illustrates the main benefit to be gained from the application of this integrated methodology. Here it was determined that no loss of statistical significance occurred when the long term IMTBF was analysed thus suggesting that some random event may have affected the system. The nature of this event may then be explored by considering the information made available by the third element of this approach.

The method therefore supports the appraisal of medium term reliability by monitoring and tracking time between failures and identifying the trends in the system's reliability performance and the current status. This information may also be useful for monitoring the longer-term effects of process improvements, machine upgrades or any other changes to operating parameters. This feature will be useful when constructing a business case for improvements, such as machine upgrades and in assessing the impact of changes in maintenance strategy, allowing engineers to focus on the worst performing systems in their section of the manufacturing facility.

4.3. *Method 3: Tracking Mean Time Between Failures TMTBF*

Following the reasoning for introducing Method 2 it was recognised by the authors that an even shorter time-base analysis method was required to identify the magnitude of the short-term deviations in reliability performance. It was believed that this short-term reliability analysis method would be of particular use to engineers responsible for the day to day plant operations and for the measurement of the effectiveness of maintenance strategies and remedial actions taken to counteract machine failures. They require immediate access to the specific data sets relevant to their section of the plant. The aim was to provide access to appropriate reliability data information to allow them to visualise and quickly identify the current status of the area under examination. This reliability tracking method would be expected to continually track the performance and allow the engineer to access any time period from data installation.

The developed reliability analysis, Method 3, was based on the standard Homogeneous Poisson Process (HPP); this analysis method is generally applied to represent the systems reliability performance in terms of the Mean Time Between Failures (MTBF) reliability indices. It was recognised that the data sets were required to be statistically identical and independently distributed for the HPP analyses method to be robust [28], a proviso that cannot normally be met with repairable machine systems due to their interdependency [17]. However as this analysis method is intended more as a comparative method between systems and is not expected to be statistically robust the assumption was made. In this application the reliability tracking method is required to access uniform time increments to allow the continuous monitoring to be an effective comparison method. For this reason it was decided that a four-week operating period based on the previously defined week number increments would be used to ensure continuity with analysis Methods 1 and 2. To make a clear distinction from the usual MTBF the derived RAM analysis approach designated as Method 3 used a new variable, Tracking Mean Time Between Failures (TMTBF) as the main operating measure. The estimate of the failure rate using this function is:

$$\hat{\lambda}_{MOD} = \frac{N+1}{T} \qquad (9)$$

Where N = number of failures and T = operating time (taken as 672 hours)

The new TMTBF measure, which is simply the reciprocal of $\hat{\lambda}_{MOD}$ can be acquired within the individual four week operating segments. The modification shown in Equation 9 is to allow TMTBF to reach a maximum of 672 hours when the breakdown level equates to zero. TMTBF is used to monitor the short term time between failures and identify the magnitude of the changes in the system's status over a four week operating period. This method can be illustrated by examining Figure 2c for the changes in the systems performance from week 36 (TMTBF = 224 hrs = 3 breakdowns) to week 40 (TMTBF = 67.2 hours = 10 breakdowns) and week 44 (TMBTF = 672 = 0 breakdowns). This analysis indicates that a problem arose in the period under consideration that caused an increased level of breakdowns. Given the complicated nature of the plant this could be due to many factors such as the introduction of a new process, new operator or the failure of other equipment in the plant. The occurrence on zero failures in the following period is also worth noting as it could be due to more closely supervised operation following a repair or to the non-operation of the plant. This again illustrates the efficacy of this integrated method as the nature and details of such a cause may be fully investigated. The fact that the integration of this method will ultimately be across the whole steel works allows for even greater knowledge acquisition as cross system analysis becomes possible.

The main purpose of this analysis was to focus attention on the operating periods which exhibit poor TMTBF reliability indices. This can be used to indicate to the area engineer the section of the process which requires prompt attention. Operators may also use this indication to instigate any repairs or modifications needed to return the system to "normal" and measure the effect of such actions. The timeliness of such actions obviously depends upon the responsiveness of the analysis method to such occurrences and this is a critical factor in justifying the application of this research. To facilitate this important feature the continuous tracking feature built into the analyses allows the necessary further monitoring of the systems response following such actions.

5 RELIABILITY ANALYSIS MODEL APPLICATION

The RAM system was developed as a tool that can be used by engineers on a week to week basis to monitor plant performance. It is very likely that the initial steps in the process of assessing reliability changes will be initiated using Method 3. The potential medium term consequences will then be analysed using Method 2 before the overall affect on long term reliability analysis will follow using Method 1. An example of the application of how these three methods can be built upon using this approach will now be presented in the context of the performance of the Strip Coilers, one of which is shown in Figure 3.

INSERT Figure 3 The Steel Strip Coiler

These are massive rotational devices which wind the finished steel strip around a central mandrel into coils of standard sizes ready for transference to further processing stations. There are several such coilers installed in the steel plant under review and the two considered here are labelled as Coiler 4 and Coiler 5. These two Coilers are of identical design, age and construction and are placed in a linear series configuration with Coiler 5 situated directly behind Coiler 4. They are intended to operate sequentially and are designed to be fully utilised when the process line is operating at full capacity. The same time period, from Week 0 to 156, is considered in the application of each of the three Methods. The failure data used in this analysis is included in Annex 1 to this paper.

5.1 Application of Tracking Mean Time Between Failures (TMTBF)

The reliability analysis system Method 3 is based upon the HPP model and uses the modified TMTBF measure as defined in Equation 5. It was developed to identify short term reliability changes affecting a sub-section of the plant to further enable the effective management and maintenance. In this context the two coilers represent a typical application; they are repairable mechanical systems which can be subject to multiple failure modes each of which can result in complicated repair or replace maintenance actions. They are also elements within the Hot Strip Mill, which is itself part of the Steelworks. Their reliability thus impacts at all levels of operation within the works and should be assured using whatever means possible.

It can be seen from Figure 4 that Method 3 is quick to react to any changes in a system’s condition and allows a comparison of the failure behaviour displayed by this system and is therefore useful for short term monitoring. It is also evident that long term trends cannot be determined using this method, thus justifying the integrated approach that utilises two higher level methods.

In this case the TMTBF behaviour for Coiler 5 shown in Figure 4a indicates that it experienced a significant number of breakdowns during the period Weeks 108 to 140 (Zone 1 Figure 4a) with a minimum TMTBF value of 67 hours. There was considerable improvement in Weeks 148 to 156 (Zone 2 Figure 4a) when the value rises to 336. In both cases an investigation may be justified seeking the causes of such responses. The short time base of the calculation of the TMTBF used in this method means that it has a sensitive response to disruptions, including events such as the operating stoppage periods in Week 104 and can be expected to react similarly to changes in performance following repair or maintenance actions. It is also capable of indicating the loss of data reporting functions in time for their restoration prior to any significant information losses.

The application of this method can be further illustrated by the analysis of Coiler 4 behaviour shown in Figure 4b. It can be recognised that Coiler 4 also appears to undergo several different patterns of behaviour. The features that can be identified from this graph are the major variations in the recorded TMTBF during its initial first 52 weeks (Zone 3 Figure 4b) and a very poor reliability performance in the weeks prior to Week 144 (Zone 4 Figure 4b) with the TMTBF reaching a lowest value of 19 hours. The consideration of the possible causes of this behaviour is presented in section 5.3 below.

INSERT Figure 4 Output from Method 3 Tracking Mean Time Between Failures

Overall the method allows an informed opinion to be drawn regarding the operational status of the system from within the specific plant locations. It is clear that the method does not provide any real long term indications of performance, such as trends. As such trend related data, such as the cumulative failure performance are not included.

5.2 Application of Incremental Mean Time Between Failures (IncMTBF).

This method deploys the PLP model developed in Equations 1 to 4 to monitor reliability using the incremental assessment of performance as data is added for each 672 hour period to produce a new measure; IncMTBF. Since this method is applied sequentially over the entire period being considered it is presented in combination with the assessment of cumulative failures, which are recorded with the IncMTBF as shown in Figure 5a, which presents the analysis of Coiler 5. It should be noted that in this case the cumulative failure reached 135 during the displayed period. The application of a CvM goodness of fit test indicated that the PLP was a “good fit” to the entire Coiler 5 data set, suggesting that the method could be deployed in the assessment of current and potential performance of the system. When reviewing the overall analysis of this system it can be seen that there were major fluctuations in performance being recorded up to Week 40. These fluctuations did not result in the loss of statistical significance of the model being applied and thus could be said to be arising due to random variations rather than to a significant change in overall behaviour. After this period the system performance is represented as predominantly deteriorating at a slow uniform rate.

INSERT Figure 5 Output from Method 2 Incremental Mean Time Between Failures

This RAM analysis (Method 2) indicates a potential method for visualising trends in the failure data sets, as can be seen in the medium term improvement in system performance which is captured within this graph. This can be illustrated by again considering Zone 1 on Figure 5a which shows a peak in IncMTBF of 541 hours. In addition more moderate deviations in system performance can be visualised in the graph. For example, the performance deterioration trend changing to an improvement trend depicted between Weeks 44 and 57 (Zone 2 Figure 5a) and the reliability improvement trend depicted between Weeks 80 to 104 (Zone 3 Figure 5a). Again it may be noted that this behaviour did not cause a loss of statistical significance of the applied model and thus the application of the method and claimed deterioration and subsequent improvement in performance was justified. It will be shown later that the response rate of this analysis method is considerably faster than the application deployed in Method 1; this is a useful function in identifying trends in failures at a level that can be combined with Method 3 to allow in-depth performance analysis.

The benefits of this method can be further supported by the analysis of Coiler 4 shown in Figure 5b, from which it can be easily recognised that this system appeared to experience different patterns of behaviour. The analysis reveals a predominately improving trend from Week 20 to 68 (Zone 4 Figure 5b), followed by a slowly deteriorating trend (Zone 5 Figure 5b) and a severe deterioration trend from Week 136 (Zone 6 Figure 5b). It was concluded that the major discernable trends in failures in this system indicated the overall deterioration of operational performance. This can be confirmed when comparing the decrease in IncMTBF with the increase in cumulative failures, which reach 254 by the end of Zone 6 of Figure 5b. This analysis method’s fluctuation with the relevant incremental breakdown numbers recorded during each reporting interval allows it to be useful in identifying performance trends in the operating system. The CvM test was applied and that this data set was not statistically significant. The assumption can be made that there are special causes in this operating system, which may be linked to the overall operating strategy, operator influences or changes to machine condition. This diagnosis of which special cause was present was determined in conjunction with the application of Method 1, which is outlined in the next section.

5.3 Application of Instantaneous Mean Time Between Failures (IMTBF).

This method deploys the PLP model developed in Equations 1 to 4 to monitor reliability using the assessment of the conventional IMTBF measure. The representation of the Coiler 5 IMTBF analysis is given in Figure 6a. The goodness of fit tests for this system indicated that this data set was statistically significant with a CvM calculated value of 0.20 against the maximum allowable value of 0.22. The Military Handbook test applied to this data confirmed that this was the case with the calculated value being the same as the required value (214). This confirmed the veracity of the applied model and that the application of the Method 1 is valid for this data set.

It can be seen that the system is undergoing a steady deterioration in its reliability status from the start of this data logging exercise. This “negative” reliability growth situation is identifiable by the steady rise in cumulative failures, with 135 recorded failures over the three year period. This indicates that the model can be deployed to detect that improvements are required to reverse this performance trend.

The trend indentified in Figure 6a appears to be repeated in Figure 6b. However, assessing the statistical significance of Coiler 4 failure data for the same period produced a very different result. The CvM test returns a calculated result with a value of 1.22 against the allowable value (0.22), indicating that in this case the application of the method is not statistically significant. Once again this finding was confirmed by the Military Handbook test, with a calculated result of 401 against the required value of 430. Even though Coiler 4 experienced a higher number of cumulative failures (254) over the three year period this is a surprising result given that the two systems are of identical design and operate within very close proximity to each other.

INSERT Figure 6 Output from Method 1 Instantaneous Mean Time Between Failures

Figure 6a indicates that Coiler 5 experienced an almost linear consistent rise in failures over the three year operating period, whilst Figure 6b for Coiler 4 shows periods of significant deterioration, for instance between Weeks 20 to 24 (Zone 1 Figure 6b), with a second period of deterioration in the system performance occurring between Weeks 132 and 144 (Zone 2 Figure 6b). A possible explanation for this behaviour is that during this period the coiler experienced severe difficulty with the throat guide controlling the entry of the strip, with twelve stoppages assigned to it during a five day period. It is possible to consider that these stoppages could have been reduced to one fault, but this judgement cannot be applied retrospectively without further information. Further issues arise in the data recording scenario in that these failures were recorded as multiple entries of 3, 5 and 4 in each case. It is again possible to consider that such stoppages should have been recorded using one entry. In all some 24 possible cases of multiple entries were recorded for Coiler 4 with 14 for Coiler 5. This will have an adverse effect on the statistical significance of the accumulated data set.

These deviations in Coiler 4 failure patterns are what caused the goodness of fit (CvM) test to report that the data was not statistically significant and therefore the analysis may be initially viewed as “not fit for purpose”. This would normally invalidate the application of PLP based reliability assessments and predictions; it is also one of the major reasons why such techniques should not normally be applied in this context. However this “negative” result can be viewed as being a positive input in this approach because it can be used to trigger deeper analysis. Further examination of the failures of these two identical systems indicated IMTBF figures that were in the ratio of approximately 2:1 with Coiler 5 experiencing an IMTBF value of 152 hours at the end of the reporting period (Week 156) whilst Coiler 4 returns an IMTBF value of 82 hours for the same period. The PLP has described the deterioration as occurring with a uniform steady state decline in reliability growth. When examining the relative changes in cumulative failures on both systems it is relatively simple to identify the main differences in their performance.

In this case consideration of the cumulative failures can identify where outside “special causes” such as the Coiler throat problem and data recording scenarios outlined above have influenced the apparent performance of the system. Further research into the operation of the mill indicated that these changes in the respective failure rates were also a reflection of the working pattern placed upon Coiler 4 by the operating process. As Coiler 4 is situated in front of Coiler 5 it is easier to divert all manufactured product onto this Coiler. This appears to have been the strategy employed in this operating period; it was found that Coiler 4 was the designated coiling unit and had thus taken on most of prescribed steel coiling activity during the observed periods and was therefore operating under different and more severe working conditions.

These results are indicative of the widely different operating regimes which can be imposed on two identical systems which were originally designed to operate at similar work rates. The corresponding effects of a disparate work load on their failure patterns are mirrored in their respective goodness of fit tests. The additional analysis methods proposed in this reliability model are intended to enhance the ability of the deployed analysis system to identify if any special causes are impinging on the systems operation as they arise during the period rather than with the benefit of hindsight.

6 DISCUSSION

In undertaking the review of research to support this work it was identified that there are no readily identifiable long-term applications of reliability modelling techniques suitable for repairable mechanical systems being applied within the world-wide manufacturing environment. One of the main reasons for this is the disparity of the repairable systems under review and the range of operating conditions seen by these systems over a long-term manufacturing period. This means that many of the failure data sets produced are not statistically significant, a factor which makes the failure data sets unsuitable for many analysis techniques. The RAM method can be applied to such systems and has been engineered specifically to meets these requirements. This research has shown that the three level analysis approach used does work in these cases and will react to changes in system operation.

This is a novel approach to the reliability analysis of repairable systems. It is the authors' opinion that this feature has been one of the major constraints on the wider application of reliability analysis techniques for repairable systems to date. The analysis methods are integrated to form a single system and it is through the combined use of all three that a measured response to a change in the system's reliability status may be constructed. The nature of the analysis and monitoring achieved is synergistic, with the end result being more significant than just the combination of the three methods. The authors therefore consider that this has the potential to become an important advancement of reliability research.

It has been shown through the initial investigations of the data sets under review that not all of the results of the reliability analysis modelling are proven to be statistically significant. Through the use of the installed goodness of fit tests it is possible to identify the significant data sets and thus isolate the data that lie outside of the anticipated behaviour and by association the incidents causing the change in reliability. This allows the engineer to apply his experience and knowledge of the machinery to determine the root cause responsible for the loss of significance. This can lead to the installation of a countermeasure such as a change to the operating pattern, an upgraded machine or revised failure recording method. Further system analysis such as a reliability centred maintenance (RCM) activity may be required if there is no obvious reason identified. It is intended that successful implementation of these countermeasures can be monitored and confirmed by the deployed methods.

The use of a uniform analysis method is additionally helpful in allowing the calculated reliability analysis figures to perform a comparative analysis. This can highlight, as in the cases of Coiler 4 and Coiler 5, the differences in working patterns and their corresponding effects on system reliability. It is recognised that there are alternative analyses methods that may be more suitable for the reliability monitoring of certain process areas. However the inclusion of additional analysis methods impinges on the ability to perform cross comparisons between separate systems.

However for this reliability modelling method to be truly effective there remains the considerable requirement of manipulating of the analyses methods to ensure the simplicity of operation with the capability to provide readily identifiable analysis results whilst supporting the ability to perform a deeper investigation into the analyses to withdraw root causes etc. In this implementation this is facilitated through the construction of a semi- automated analysis model. The main goal of this research was to identify and construct a reliability analysis model which can be utilised across the whole steelworks plant. The model is expected to be transferable to alternative operating areas with the minimum of modification and access the operating sections own failure recording databases. The derived RAM system was constructed using as a series of linked spreadsheet workbooks within which visual basic macros performed the required operations. The RAM system performed the analysis of the failure data sets following the three methods outlined in this paper. It was applied to other areas in the plant as required; the system in effect acted as a template to accommodate the model’s future application to all other business areas.

The model was designed to be operated from a front panel which controls the application of the analyses and the operating methodologies needed. The process starts by initialising the acquisition from the database of failure information relating to the Steelworks area under consideration; the front panel interrogates the main database and is populated with the relevant failure data sets and transfers this to the RAM system for the calculation of the reliability values. Each calculated value is transferred back to populate the front panel workbook. This process continues until all data sets have been analysed and the workbook is fully populated with all of the required reliability values. The program then automatically populates several reliability monitoring spreadsheets with the requested reliability indicators. Additional detail can be obtained through operating a detailed analysis macro which enables multiple graphical representations of the systems failure performance and applies goodness of fit tests to indicate if the selected failure data set is statistically significant. This process is automated but is instigated by the engineer undertaking the assessment.

The calculated results for the IMTBF, IncMTBF and TMTBF analysis methods are sequenced in three rows which are relevant to each operating area, as shown in Figure 7 which depicts the area of RAM output for the Coilers. The Front Panel controls all programs operation through the embedded buttons or drop down tables, which initiate the relevant macros when operated. It is designed to allow the worksheet examiner to easily identify any major deviations in the systems operational reliability status. The cell formatting is in the form of a “traffic light” system currently installed across the plant. The control parameter is set at +/- 5%, with identified reliability improvements flagged in green and reductions in red. The results for the three analysis methods are presented in columns which are constructed relevant to the four-week operating period. The current worksheet is designed to contain ten years data analysis results covering the period from Week 0 of 2007 up to Week 52 of 2016.

INSERT Figure 7 Extract from a populated Front Panel worksheet for Coilers 4&5

The process mimic worksheet for the section including the Coilers is shown in Figure 8. This was constructed so that the engineering staff could view a one page schematic view of the current reliability status of the operating process at the hot strip mill. This schematic includes all of the operating areas within this manufacturing unit. These are predominantly presented in a series arrangement with the support services depicted as running parallel to the main manufacturing process.

INSERT Figure 8 Process Mimic with area IMTBF reliability summaries

Situated underneath the icon depiction of each area is located a reference box which displays the relevant time between failures for that area when the sheet is activated. This worksheet contains three drop down tables which allow the process mimic to be updated as required, all time between values in the process mimic adhere to the same colour code arrangement installed in the front panel worksheet. This diagram is intended to be used as a comparator to other manufacturing areas. This is an evolutionary development in the use of calculated system reliability values. This diagram will allow high level engineering staff to compare the overall reliability figures of one manufacturing area against a competing process or even competing manufacturing plants. This could assist senior management in identifying a maintenance strategy which will be cost effective and could improve overall process efficiency.

The importance that the integration of this information offers to plant management cannot be overstated. Whilst it is possible to attempt a global plant wide approach to asset management the nature of the behaviour of numerous systems and sub-systems make this a very complex task. The timely provision of detailed performance and failure information is vital and the deployed system can play an important role in making such information available at all levels. The integration of this information in a single system can focus attention on under (or indeed over) performing areas with a view to tackling real problems and making real improvements. Not least of the attributes of this approach is the data capture, analysis and testing that it supports, thereby removing the load for such tasks from maintenance staff and allowing them to concentrate their efforts where the most return can be achieved.

7 CONCLUSIONS

The RAM system was developed to monitor plant wide performance. This was to be based upon the construction of a historical reference to the processes reliability behaviour from previous operations. This information was then to be the basis of a reliability monitoring method indicative of system changes or identifying apparent trends in the system’s behaviour. The model and system engineered to support it has been shown to operate effectively and will:

- Identify the effect of different operating conditions on similar machinery.
- Identify performance differences between different machines performing similar tasks.
- Identify discrepancies in maintenance regimes and their corresponding effects on similar machinery.
- Identify the differences in OEM quoted reliability figures and the calculated machine reliability indices obtained through the machine’s working life.

The analysis model works in a retrospective manner and it must be recognised that, due to the limitations of the statistical significance requirements, the analysis model should not be used for reliability performance prediction. It must be accepted that, for reliability prediction the model can only be applied if the goodness of fit test indicates statistical significance for the whole data set from model inception. Even under such conditions it is necessary to monitor the performance of the system to account for special causes of failure.

The application of this analysis model to additional sections within this steelworks will allow this comparative aspect of the analysis model to be expanded. This will allow the identification of the most suitable machinery and the most effective operating parameters for specific applications. In addition the most effective maintenance regimes can be identified and develop to allow a “best practice” regime to be engineered.

This three level RAM approach will allow manufacturing facilities to identify trends in reliability data and any disruptive influences on their manufacturing processes. This approach utilises advanced spreadsheet capabilities to simplify the reliability analysis techniques. The automation of the reliability analysis spreadsheets allows long term monitoring of reliability trends which can confirm or disprove any remedial actions. This will confirm that the root cause of failures has been identified and the correct remedial action installed. The installation of a short term analysis method into the RAM method will expand the use of these techniques into the toolkit of plant engineers and facilitate their use by the engineers in their day to day operational toolbox. This is an investigative approach to data analysis that is not currently used within the manufacturing environment.

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Annex 1. Coiler Failure Data

Coiler 4 Breakdown data

Hours to Breakdown

730.4	776.2	776.4	923.4	1149.8	1130.6	1512.6	1660.1	2089.2	2144.0	2208.9	2296.2	2368.2
2564.1	2575.1	2615.4	2626.2	2635.0	2726.4	2728.0	2731.8	2789.7	2815.6	2867.7	2880.0	2862.2
2895.3	2937.6	2939.1	3105.6	3117.7	3130.9	3131.3	3286.1	3359.0	3363.2	3477.4	3744.3	3856.8
3917.3	3992.3	4088.2	4248.8	4777.7	4833.6	4893.6	5289.0	5289.3	5542.5	6041.1	6168.3	6245.8
6272.4	6374.9	6517.2	6520.3	6520.8	6522.4	6524.6	6538.6	6573.9	7655.3	7689.6	7734.2	7759.0
7767.4	7876.2	8245.9	8312.8	8313.3	9229.2	9422.8	9463.7	9518.7	9571.6	9965.2	10023.8	10313.1
10954.1	11680.9	11838.0	11887.7	11967.8	11971.0	12158.2	12249.4	12352.5	12398.9	12413.0	12492.6	12496.7
12545.5	12856.4	12947.1	13293.1	13293.6	13607.4	13634.3	13636.9	13637.3	13687.8	13907.3	14240.8	14248.2
14249.8	14291.7	14311.9	14314.3	14430.7	14455.0	14583.2	14584.0	14600.3	14614.4	14813.5	14868.0	14858.7
15007.0	15069.6	15199.2	15205.8	15244.3	15603.4	15893.0	16044.1	16046.7	16079.2	16293.4	16478.1	16479.2
17916.8	17998.7	18012.6	18347.7	18588.1	18690.2	18706.0	18900.1	18946.9	18949.8	19039.8	19260.2	19327.9
19409.3	19585.8	19833.2	19843.3	19825.3	19826.5	19858.0	19872.6	20084.0	20064.8	20157.0	20229.2	20230.4
20233.1	20267.7	20386.5	20498.2	21103.2	21414.5	21439.0	21777.0	22129.9	22130.4	22131.2	22132.2	22238.9
22245.5	22281.7	22283.2	22424.5	22435.6	22419.3	22422.6	22472.5	22483.0	22613.4	22722.5	22724.8	22852.8
22906.0	22953.3	22999.7	23012.7	23027.1	23193.9	23197.1	23222.3	23223.9	23225.9	23228.2	23229.2	23230.0
23231.0	23209.0	23240.4	23245.7	23268.4	23277.3	23279.1	23259.2	23261.7	23317.3	23335.4	23338.7	23340.3
23351.3	23373.9	23387.2	23398.0	23504.1	23515.8	23499.9	23601.4	23611.1	23672.3	23793.9	23806.6	23807.2
23784.1	23939.3	23944.3	23946.8	23947.6	24022.2	24000.3	24058.3	24116.2	24118.0	24172.2	24209.5	24196.5
24232.5	24315.4	24349.9	24636.9	24717.4	24788.4	24841.3	25045.7	25096.5	25151.1	25571.8	25575.0	25729.6
25760.8	25885.7	25886.2	26039.2	26016.8	26146.6	26266.2						

Coiler 5 Breakdown data

Hours to Breakdown

263.4	1128.2	1393.9	1561.4	1562.8	1779.8	1983.3	2131.0	2131.1	3271.0	5027.2	5287.6	5288.9
5327.8	5304.6	5305.2	5764.1	5892.8	6132.6	6222.1	6324.9	6495.4	6983.3	7323.9	7324.4	7415.8
7441.7	7761.0	7863.0	7875.6	7914.4	8091.1	8117.7	8153.3	8264.6	8530.7	8727.7	8868.2	8868.4
9378.5	9890.1	10102.2	10102.5	10959.0	11195.4	11361.7	11782.2	11786.9	11851.8	11876.9	12393.6	12394.3
13078.5	13125.4	13420.3	13422.5	13451.9	13593.7	13607.0	13737.9	13731.0	13733.5	13774.4	14082.2	14086.5
14101.4	14092.8	14094.0	14614.1	15199.1	15548.6	15570.9	15557.0	16065.9	16288.2	16293.2	16426.1	16479.1
8727.7	17971.0	17971.2	18269.7	18301.1	18306.8	18391.0	18415.1	18424.0	19018.3	19029.6	19330.9	19336.2
19361.6	19406.9	19413.5	19470.2	19596.1	19736.5	19766.7	19861.9	20506.6	20567.3	20820.9	21044.9	21145.9
21379.2	21365.1	21826.0	21886.3	22020.2	22417.4	22443.8	22445.1	22502.1	22569.6	22613.8	22645.2	22645.8
22724.6	23009.8	23015.5	22994.8	23159.5	23159.8	23188.7	23295.9	23732.7	23769.0	23801.8	23978.8	24080.6
24084.9	24404.5	24469.4	24899.2	25760.8								