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An Alternative Maintenance Technique to Improve the Maintenance Decisions of Production Machine System

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Abstract

This paper proposes an alternative maintenance technique called output-based maintenance (OBM) for improving the maintenance decision making of production machine system/sub-system. OBM technique generally used the outside-to-inside (OTI) approach in identifying and solving the maintenance problem. The basic idea of OBM technique is the used of machining output measure (e.g. product quality characteristics) as the main monitoring parameter to indicate the failure process of the machine system/sub-system. Therefore, more realistic process of maintenance decision making can be made via machining output measure trend prediction. This paper firstly discusses the needs an alternative technique for solving maintenance problems and followed by introducing the concept, aims and benefits of the proposed technique. Then, the implementation model of decision support by adopting the OBM technique namely output-based decision support maintenance model (OBDSMM) is presented. The OBDSMM is validated via a real case study carried out at pulp manufacturing industry. This paper concludes with the summary of the unique features of OBDSMM and possible future research works.

Keywords
Maintenance decision making, production machine system, condition-based maintenance, output-based maintenance

1. Introduction

In manufacturing industry, maintenance is one of the support functions that have become increasingly important, especially in production machines with high capital investments [1]. Maintenance plays an important role in keeping availability and reliability of the machine, product quality, and safety requirements. In general, maintenance broadly can be classified into Corrective Maintenance (CM) and Preventive Maintenance (PM) strategies [2-4].

Corrective Maintenance (CM), also known as Run-To-Failure or reactive maintenance is a strategy that used to restore the machine to it required function after it has failed [5]. However, this strategy reflects to high machine downtime (production lost) and maintenance (repair or replacement) costs due to unplanned maintenance [6]. Therefore, an alternative of CM strategy is Preventive Maintenance (PM) strategy. The concept of PM is to perform the maintenance activities before the equipment fails [7, 8]. In other words, the application of PM strategy is the main key to maximise the efficiency of production process by minimising the unplanned maintenance (corrective maintenance). In relation, maintenance research towards PM strategy is actually concern with decision making process to determine what, where and when the appropriate maintenance should be performed.

Many maintenance techniques have been proposed and applied for solving and making the maintenance decisions and one of them is condition-based maintenance (CBM). CBM (UK terminology) or also known as predictive maintenance (US terminology) is a modern maintenance approach that has been introduced in industrial application in 1975. The heart of CBM is the condition monitoring process, where signal is continuously monitored by using certain type of sensor or other appropriate indicator [9]. Therefore, maintenance activities (e.g. repair or replace) are performed only "when needed" or just before failure [10]. The motivation of CBM is that 99 per cent of the component failures are preceded by certain signs, conditions, or indications that a failure was going to occur [11]. In general, the main goal of CBM is to perform a real-time assessment of component condition in order to make maintenance decisions, consequently reducing unnecessary maintenance and related costs [12].

Although research in maintenance has evolved for the last decades, still there is a need to rethink the way maintenance is carried out [13]. In other words, the new or alternative technique is still needed to improve the maintenance decision making process, thus the proper PM program can be implemented. Khanlari et al [14] defined proper maintenance as very few corrective maintenance events, while performing as little as possible PM actions [15]. Therefore, the general goal of this paper is to discuss the need of alternative technique to improve the maintenance decision. In relation, this paper introduced an alternative technique for production machine maintenance called output-based maintenance (OBM) and proposed the decision support implementation model based on OBM technique namely output-based decision support maintenance model (OBDSMM).

2. The Need of Alternative Maintenance Technique

In the literature, the application of CBM technique in solving maintenance problems and decision making is well reported. For example, Lu et al [16] proposed a predictive condition-based maintenance model based on monitoring, modelling, and predicting the system deterioration. Predicting the system deterioration is performed by adopting a state-space model and Kalman filtering technology. From the proposed model, maintenance decisions are made according to the predicted degradation conditions and associated cost factors to enhance the profit produced by the system. Baek [17] presented a maintenance decision making model based on CBM called intelligent CBM scheduling model to solve sequential decision-making problem. The proposed model integrates an incremental decision tree learning method and deterministic dynamic programming techniques in order to select the best safe state in terms of the total maintenance cost. Ambani et al [18] applied the CBM approach for solving maintenance problem of multiple-machine cases. They developed a continuous time Markov chain degradation model and a cost model to quantify the effects of maintenance on a multiple machine system. An optimal maintenance policy for a multiple machine system in the absence of resource constraints is obtained. A case study focusing on a section of an automotive assembly line is used to illustrate the effectiveness of the proposed model. Tan and Raghavan [19] developed a simple practical framework of predictive maintenance (PdM) programme to schedule the maintenance activities for multi-state systems (MSS) based on imperfect maintenance policy. The principle of the programme is that the maintenance schedules are derived from a system-perspective using the failure times of the overall system as estimated from its performance degradation trends. A statistical model was derived to analyse the system degradation and estimate the replacement time of the system. Li and Nilkitsaranont [20] described the application of CBM in estimating the remaining useful life of gas turbine engines before their next major overhaul based on historical health information. Both of linear and quadratic models of regression techniques are proposed to predict the remaining useful life of gas turbine engines. Karabay and Uzman [21] discussed the application of predictive maintenance concept based on vibration measurement in monitoring and decision making. Two industrial case studies have been used to validate the proposed method. The first case study focused on fault machine rotor detection while the second case focused on the ball bearing failure detection. Niu et al [22] presented a CBM system by applying the reliability-centered maintenance mechanism to optimize maintenance cost, and employs data fusion strategy for improving condition monitoring, health assessment, and prognostics. The proposed system is demonstrated by way of reasoning and case studies. The results show that optimized maintenance performance can be obtained with good generality.

Although the application of CBM has increasingly drawn attention in industry because of its many benefit [23, 24], however it is not always easy and straight forward for it to be applied in real industry. In fact, the application of CBM should starts by understanding the failure mechanism of the target component(s). Since the main aim of any maintenance techniques towards PM strategy is to avoid the failure event (unexpected failure), then the important question is how do we actually define the failure of the targeted component(s)?, then what is the most realistic monitoring parameter can be used to indicate the actual failure process of the component (deterioration process)?. In fact, these questions are where most of the CBM application reported in the literature rarely considered. As a result, the maintenance decisions (e.g. repair or replace) that have been made might not refer to the actual perspective of the component(s) failure. For example, in production machine perspective, failure of the machine component (refers to single-component type) can be classified into two types. The first is the component towards physical failure, which the component is considered fails when its function is terminated due to physical damage (e.g. crack, broken etc). The effect of this type of failure will result the whole machining process totally stop from operation (sudden breakdown). The second is the component towards functional failure, where the component is considered fails when its function does not reaches the requirement. This type of failure may not result the whole machine system suddenly stop from operation, but the machining process output (e.g. products quality) produce by does not satisfy the requirement.

The literature reviews reveals that most of the CBM application focus only on the first type of component failure and in most cases rotating components have been studied such as bearing and gears that can be classified under component towards physical failure. Furthermore, in production machine perspective, failure of the component towards functional failure or combination of component towards physical failure is more crucial problem to be solved. The main reason is that the economic impact from these types of component failure will contribute to increase not only the internal cost but also external cost. Internal cost refers to the increase in production cost due to corrective maintenance action (unplanned maintenance), where it includes the cost of unplanned downtime, spare part delay, rework etc. Meanwhile, external cost refers to the costs claimed by customers due to unsatisfied business, for example costs of products reject, delay and reliance of customers.

In addition, the existing maintenance technique including CBM usually solved the maintenance problem based on inside-to-outside (ITO) approach. In the ITO approach, maintenance problems directly focuses on the subject inside the machine (component), where the related information (data) regarding the targeted component(s) is gathered and the data analysis/modelling is carried out towards maintenance decisions making, with the hope the whole machine system/sub-system will operate as it is required. It is supported by Chen and Jin [25] stated that traditional or conventional maintenance techniques only focused on the direct downtime or performance loss of targeted component(s). The impact of ITO approach is that the state of the targeted component(s) on machine output (e.g. product quality) is not well addressed. In addition, the failure interaction with other machinery components is always ignored.

3. Output-based Maintenance

Unlike the conventional maintenance techniques (TBM and CBM), which the maintenance problem basically solved based on inside-to-outside (ITO) approach; output-based maintenance (OBM) on the other hand, solve the maintenance problem based on outside-to-inside (OTI) approach. The motivation of this approach can be explained based on the structure of production machine system/sub-system as shown in Figure 1.

Referring to Figure 1, the machine system/sub-system usually consists of two or more components, where they are working together to perform certain machining process such as cutting, embossing, perforating, etc. In most cases (production scenario), machine will be stopped for maintenance actions due to the output of the machine such as the product quality is out of specification. For fully automate machine, this scenario directly caused by the machine itself, where one or more component(s) in the machine system/sub-system having problems and requiring maintenance. This is supported by Arunraj and Maiti [26], where there is a close relationship between machine maintenance and its output (e.g. product quality), as its output depends on the machine component condition. Therefore, from production machine perspective it is more reasonable and possible to make the maintenance decisions of machine component(s) by relating it with the machine output. In other words, by monitoring the machine output ("outside" the machine), the problem of certain component(s) in the machine system/sub-system ("inside" the machine) can be detected, thus better maintenance decisions can be made.

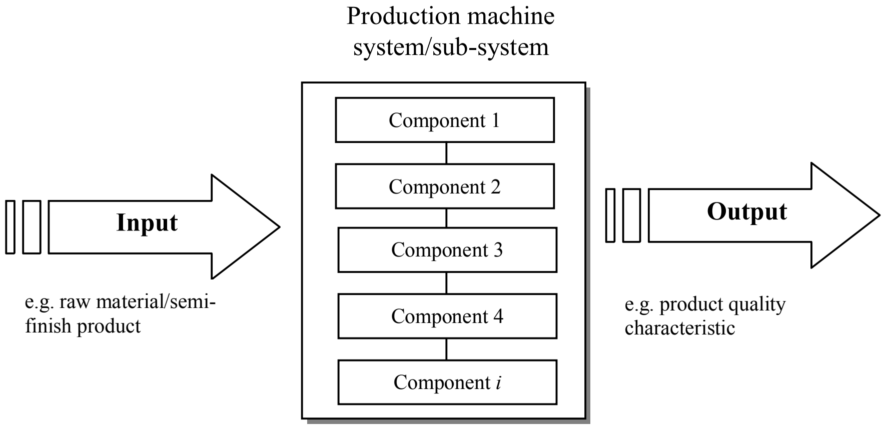


Figure 1: General process of production machine system/sub-system

The description from previous paragraph becomes the principle of OBM, where in general it actually applied the concept of CBM (based on monitoring process), but the way it solved the maintenance problems is different, which the emphasis is given on the question 'how do we actually define the equipment has fails?'. In OBM, the main keyword is the use of the machine output measure (e.g. product quality characteristics) as the main monitoring parameter to indicate the actual condition of the machine component(s) (deterioration process towards failure). Therefore, maintenance decision can be more realistic and based on the actual perspective of the machinery component failure.

In relation, even the principle idea of OBM and it potential in making better maintenance decisions is mentioned by Taguchi et al, Ben-Daya and Duffuaa [27,28], but how this idea can be applied and implemented for difference cases (e.g. single and multiple-component(s), non-repairable or repairable types and functional or physical failures) in a structured and systematic way is still missing. Therefore, the following section briefly presents the decision support implementation model by adopting the OBM technique called Output-Based Decision Support Maintenance Model (OBDSMM). The structure of OBDSMM is briefly presented in the following sections.

4. Output-based Decision Support Maintenance Model (OBDSMM)

OBDSMM is a decision support implementation model based on OBM technique. It provides the systematic guidelines not only to monitor the machine component(s) condition but also making the maintenance decisions based on realistic monitoring parameter (machine output measure). In general, OBDSMM combines the quantitative and qualitative processes, where it is broken down into three main steps. Detail of each steps are given as follows.

4.1 Step 1 – Initial Assessments

The first step of OBDSMM begins with the initial assessments. The main objective is to gain the related information that can be used for deterioration monitoring and decision making processes. This related information can be gathered from two types of knowledge sources; explicit knowledge and tacit knowledge [29]. Explicit knowledge is the information come from the report and things that well documented or stored on computers. Meanwhile, tacit knowledge is the information that collected from workers experiences. The initial assessments step comprises to the four tasks; machining process characteristics, critical equipment identification, critical equipment mechanism assessment and operational costs assessment. The summary of each task is shown in Table 1.

Table 1: Summary of four tasks in Step 1

Tasks of Step 1	Objective/significant/motivation of the task	Analysis tools/ source of information
Machining process characteristic identification	• Identify interest machining process characteristic output (e.g. cutting surface quality, sealing appearance quality etc) • Identify the components that responsible to the interest machining process • Identify the component(s) that affects to the product quality (output of machining process) characteristic	Source of this information highly rely on experience workers
Critical component(s) identification	Not all components are worthwhile to be considered for special maintenance program. Thus critical component(s) identification is required.	Total costs per year due to maintenance effects, *TC*
Critical component(s) mechanism assessment	This task is required in order to making better maintenance decision. The mechanism considered are; • **Structure type** – single-component or multiple-components • **Design type** – non-repairable or repairable • **Failure type** – functional failure or physical failure	Tree diagram presentation
Operational costs assessment	Detail estimation of maintenance costs to support the decision making process;	• Failure cost, C_f • Preventive replacement cost, C_{pR} • Preventive repair cost, C_{pr}

4.2 Step 2 - Deterioration Monitoring Process

After the initial assessments of the critical component(s) are completed, the deterioration monitoring process is carried out. The objective of this step is to set the monitoring process and analyse the related condition monitoring information to indicate the deterioration of the targeted component(s). Step 2 consists of four tasks; failure limits setup, data collection process, monitoring setup and trend analysis. The summary of each task is tabulated in Table 2.

Table 2: Summary of four tasks in Step 2

Tasks of Step 2	Objective/significant/motivation of the task	Analysis tools/ source of information
Failure limits setup	Determination the failure limits of the monitoring parameter(s)	Main monitoring parameter: output characteristic quality of machining process Vibration, sound, temperature etc.
Data collection process	Selection the type of monitoring process	Continuous monitoring Periodic monitoring
Monitoring setup	Selection the types of monitoring interface	• Single predetermined failure limits interface • Double predetermined failure limits interface
Trend analysis	Predict future deterioration trend	Traditional Trend modelling • Linear model • Exponential model • Polynomial model Exponential smoothing • Single exponential model (SEM) • Double exponential model (DEM) Advanced trend modelling • Autoregressive moving average (ARMA) • Autoregressive integrated moving average (ARIMA)

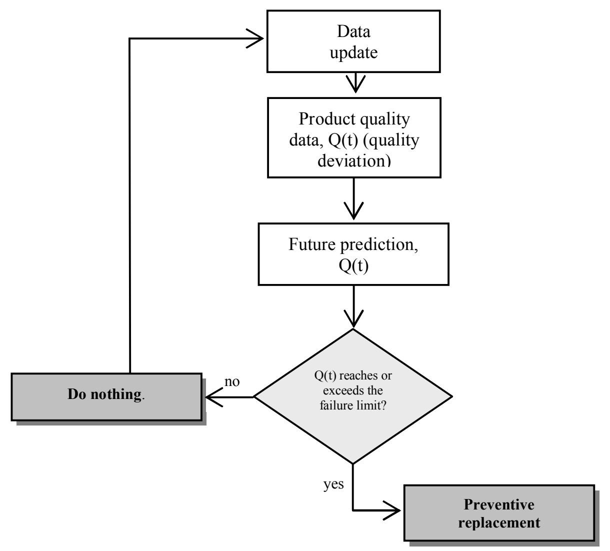
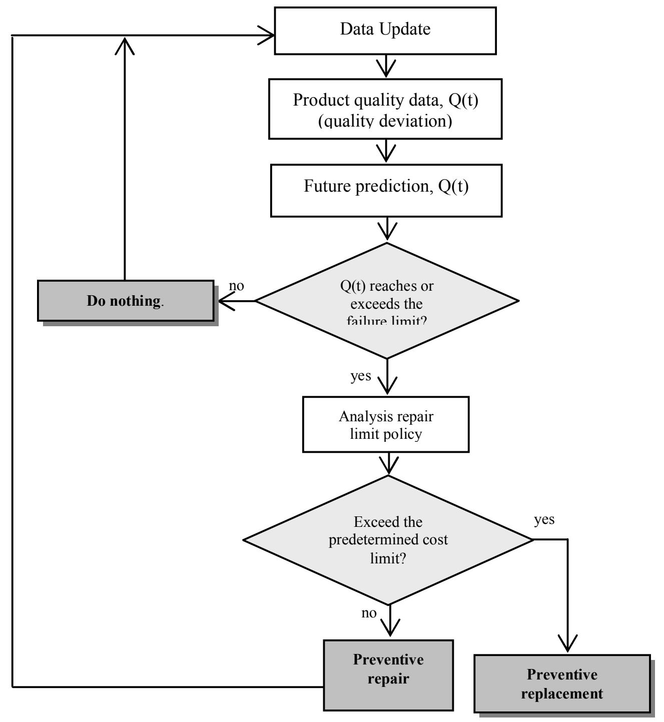
4.3 Step 3 - Decision Making Process

The final step of OBDSMM is the decision making process. The objective of this step is to interpret the information that have been analysed in previous step and propose the appropriate maintenance decision. In this step, several decision algorithms based on tree diagram approach is proposed. Three types of component(s) mechanism are considered in the decision algorithms. There are;

1. Structure type – single-component or multiple-components
2. Design type – non-repairable or reparable
3. Failure type – functional failure or physical failure

Two decision algorithms for single case component towards functional failure are given in Table 3.

Table 3: Decision algorithms for single component case towards functional failure

Single non-Repairable Component towards Functional Failure	Description
	In the OBDSMM, single non-repairable component towards functional failure is the simplest case to be solved. Since this case is the functional failure type component, thus the only data required is product quality deviation, *Q(t)*. In this case, two decisions will be decided, either do-nothing or replace because the equipment is classified as non-repairable type. The decision algorithm starts with data update process then it follows by the future trend prediction process. Referring to the diamond box, if the predicted point shows the product quality deviation, *Q(t)* will reaches or exceeds the failure limit, the decision of replacement is made, otherwise the decision of "do-nothing" is preferred. The decision of "do-nothing" means the entire process of decision making return back to the data update process.
Single Repairable Component towards Functional Failure	**Description**
	In the case of single repairable component towards functional failure, three decisions are involved; whether do-nothing or repair or replace. As in previous case, this case also deals with the functional failure type component. Therefore, the only data required that indicate the component deterioration is product quality deviation, *Q(t)*. On the other hand, since this case is classified as repairable component, the decision either to repair or replace the component is needed. Therefore, to decide the most appropriate decision (either to repair or replace) it is rational to take into account the total maintenance cost analysis based on repair limit policy. In the OBDSMM, repair limit policy is the calculation of total maintenance cost per lifecycle of the component by considering the number and total costs of repair performed along its lifecycle. The calculation of repair limit policy is shown below; Total maintenance cost per lifecycle, $T_{cost} = C_{pR} + SUM\ C_{pr} + SUM\ C_{pr}$ Maintenance decisions based on repair limit policy; Predetermined limit, T_{cost} =/> C_f If the total maintenance cost reaches or exceed the failure cost limit, then the decision of preventive replacement is preferred. Otherwise, the decision of preventive repair is carried out.

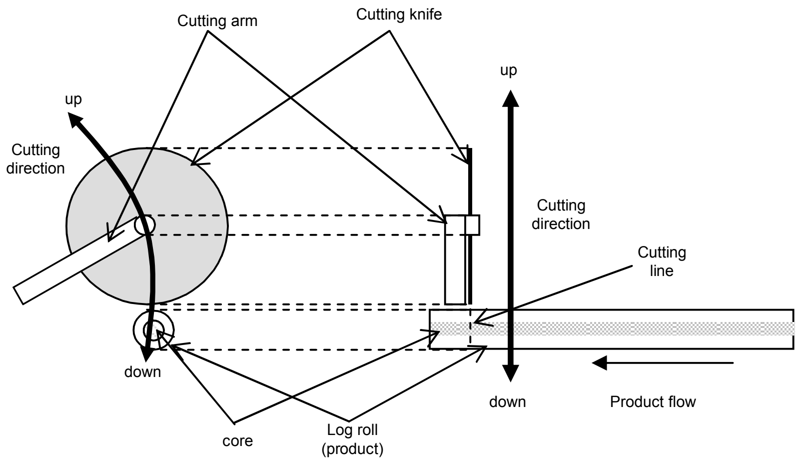
5. Case study

In order to validate the OBDSMM, an industrial case study at pulp manufacturing industry has been carried out. The interest machining process of the case study is on cutting process, which the function is to cut the semi-finished product called log roll to the finished product called final roll to a specific size (length) and quality (surface appearance) as shown in Figure 2.

(a) Log roll – Semi-finished product (b) Final roll – Finished product

Figure 2: Semi-finished and finished products

The schematic view of the cutting process mechanism is shown in Figure 3. The cutting knife is the main component responsible for the cutting process. It is supported by a cutting arm and a bearing. In this process, the cutting knife can be considered as a high speed rotating component that powered by electric motor and continuously moves up and down directions for cutting the log roll.



a) Side view b) Front view

Figure 3: Schematic views of the cutting process

The summary of results performed in Step 1, Step 2 and Step 3 of OBDSMM are given in Table 4. Referring to Table 4 of Step 1, the case study of cutting process basically focused on the surface appearance quality of the finished product as shown in Figure 2(b), which it is the result of cutting process. Next, the machinery components that have an affect to the surface appearance quality were identified, there are cutting knife, bearing of cutting holder and grinding stone. Through the critical analysis task, which is carried out based on total maintenance costs calculation per month it is found that cutting knife is the most critical component to be considered for further analysis. It is because more than 70% of the total maintenance costs of the cutting machine are contributed by the cutting knife replacement cost. Mechanism assessment of cutting knife is the next task of Step 1 to be carried out. Cutting knife is classified as single, non-repairable component towards functional failure. Since the cutting knife is classified under non-repairable component, the operational costs assessment is not required.

Table 4: OBDSMM validation summary

Step 1 – Initial Assessment	
Machining process characteristic identification	The interest machining process is cutting process with emphasis on the quality of surface appearance of the finished product that results from the cutting process. Components that affects the surface appearance quality of finished product are; • Cutting knife • Bearing on cutting holder • Grinding stone
Critical component(s) identification	Cutting knife
Critical component(s) mechanism assessment	Non-repairable component Single-component Component towards functional failure
Operational costs assessment	-
Step 2 – Deterioration Monitoring Process	
Data collection process	Data monitoring method - Periodic monitoring Data require - surface appearance quality checking Data type – attribute type Data measurement - Scale basis; Acceptance: 1= very good, 2 = good, 3 = bad Reject: 4 = bad
Failure limits setup	Cutting knife is considered fail when the surface appearance quality reaches or exceeds the scale of 3.
Monitoring setup	Single predetermined failure limit interface
Trend analysis	Double exponential smoothing model
Step 3 – Decision Making Process	
Decision algorithm	Single non-Repairable Component towards Functional Failure as given in Table 3

In Step 2 under the data collection process, the data required is the surface appearance quality of the product (final roll). Periodic monitoring is suggested as the data collection method, where every two hours of operating time, 20 samples were randomly selected from production line. Since the data of this case study is classified under attribute type, the evaluation of surface appearance quality based on scale basis is used (refers to Table 4). In relation, the failure limit has been setup as the cutting knife is considered fail when the surface appearance quality reaches or exceeds the scale of "3". The next task of Step 2 is determined the single predetermined failure limit as the monitoring interface to be used. The double exponential smoothing model (DES) model is applied for the surface appearance quality trend monitoring and analysis. The equations of DES model are as follow:

$$L_t = \alpha\, Y_t + (1 - \alpha)\, [L_{t-1} + T_{t-1}] \quad (1)$$

$$T_t = \gamma\, [L_t - L_{t-1}] + (1 - \gamma)\, T_{t-1} \quad (2)$$

$$\acute{Y}_t = L_{t-1} + T_{t-1} \quad (3)$$

Where, L_t is the level at time t, α is the weight for the level, T_t is the trend at time t, γ is the weight for the trend, Y_t is the data value at time t, and $\acute{Y}_t$ is the fitted value, or one-step-ahead forecast, at time t. Based on the result of future trend forecasting of surface appearance quality, the decision algorithm for the case of single, non-repairable component towards functional failure is used for maintenance decision making. Figure 4 shows the result of future trend forecasting of surface appearance quality from one to five-steps-ahead forecasted. Based on the proposed decision algorithm, one to four-steps-ahead forecasting suggested the "do-nothing" decision. This decision represents the cutting knife is in good condition and still can be used in operation (cutting process). At five-step-ahead forecasted, the trend of surface appearance quality shows it will reach the predetermined failure limit and based on the decision algorithm procedure, the decision of "preventive replacement" on the cutting knife is suggested to be performed before the monitoring time at five-step-ahead forecasting reaches.

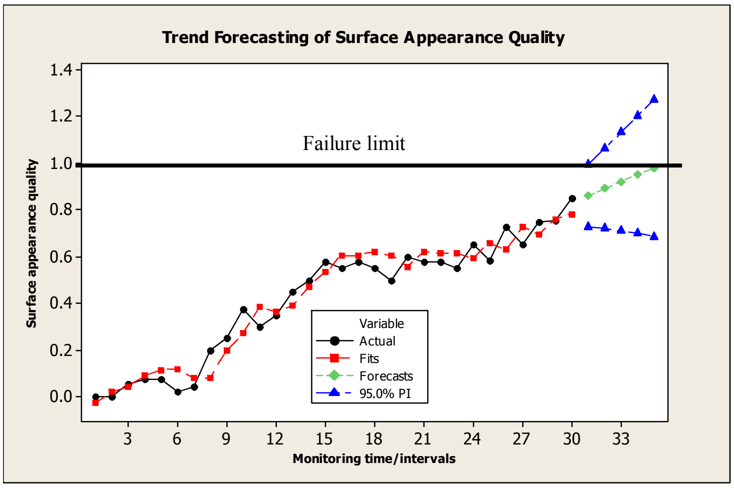


Figure 4: Future surface appearance quality trend forecasting

6. Conclusions

In this paper, an alternative maintenance technique called output-based maintenance (OBM) for production machine system/sub-system has been introduced. The main principle of OBM is that the output machine measure (e.g. product quality characteristic) becomes the main monitoring parameter to indicate the machinery component(s) condition as well as making maintenance decision based on realistic failure perspective. As follows, the implementation of decision support model based on OBM technique namely, output-based decision support maintenance model (OBDSMM) is proposed. OBDSMM is structured with three main steps; initial assessment, deterioration monitoring and decision making processes. A simple industrial case study at a pulp manufacturing industry has been presented to validate the OBDSMM. The features and possible advantages of OBDSMM are summarised as below;

1. OBDSMM is a comprehensive implementation model not only to monitor the machinery component(s) but also making the maintenance decisions based on actual failure perspective of production machine (output machine measure such as product quality).
2. OBDSMM applied the OBM technique, which OBM is a technique for solving maintenance problem based on outside-to-inside (OTI) approach.
3. OBDSMM is able to decide the right maintenance decision not only to minimise the maintenance costs but also minimise the production machine in producing unsatisfied output such as rejected product quality.
4. OBDSMM considered difference machinery component(s) characteristics in making the maintenance decisions includes single and multiple component(s) cases, repairable and non-reparable types, and functional or/and physical failure types.
5. OBDSMM provides simple decision making algorithm by applying the decision tree diagram approach, which it is not only simple but also easy to understand.

The future works from this paper is to develop the decision algorithms for multi-components cases and validate the OBDSMM for other some industrial case studies. In relation, the effectiveness of OBDSMM can be maximised by integrating it with computerised monitoring system such as visual quality inspection system to increase the accuracy of data monitoring.

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