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Optimization of Productivity through Reliability Centered Maintenance in Agro-Based Industries

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Abstract: *The success of livestock farming is largely dependent on the continuous supply of good quality nutritious feeds at competitive price. Feed alone constitute about 60-70 per cent of total cost of production of livestock products. Therefore, it needs more attention though other factors are also important for remunerative return from livestock enterprises. RCM is a very useful tool in industries with strong constraints as regards users and safety, but in spite of being a standardize approach RCM can be adapted to particular constraints and requirements of the industry where it is applied. The concept of Reliability-Centred Maintenance (RCM) is applied to the Feed Processing Unit. The executing RCM workgroup includes an owner and operator of the analyzed Feed Plant, a maintenance service provider, a provider of condition-monitoring services and Feed Plant component supplier as well as researchers at academic. Combining the results of failure statistics and assessment of expert judgment, the analysis is focused on the most critical subsystems with respect to failure frequencies and consequences: the Hammer Mill, the Pellet Mill, the electrical system and the hydraulic system. The study provides the most relevant functional failures, reveals their causes and underlying mechanisms and identifies remedial measures to prevent either the failure itself or critical secondary damage. The study forms the basis for development of quantitative models for maintenance strategy selection and optimization, but may also provide a feedback of field experience for further improvement of Feed Plant design.*
Keywords: *Feed Processing, Reliability, Maintenance, RCM*

I. INTRODUCTION

The reliability centered maintenance (RCM) concept has been on the scene for more than 20 years, and has been applied with considerable success within the aircraft industry, the military forces, the nuclear power industry, and more recently within the offshore oil and gas industry. Experiences from the use of RCM within these industries show significant reductions in preventive maintenance (PM) costs while maintaining, or even improving, the availability of the systems. According to the Electric Power Research Institute (EPRI) RCM is:

> *"A systematic consideration of system functions, the way functions can fail, and a priority–based consideration of safety and economics that identifies applicable and effective PM tasks."*

The focus of RCM is hence on the system functions, and not on the system hardware.

1.1 RCM Conceptual Model

Most of the available PM models are based on the assumption that; (1) only single units are considered, and that (2) the cost of a single unit failure can easily be quantified in (discounted) monetary units. In RCM we have to consider the entire PM program, i.e. several units simultaneously. It is further required to consider failure consequences, which cannot be measured directly in monetary units. In the present paper, we will split the possible failure consequences into the following four consequence classes:

S: Safety of personnel
E: Environmental impact
A: Production availability
C: Material losses (costs)

1.2 Steps of a RCM Analysis

The RCM process comprises the following steps:

1. Study preparation
2. System selection and definition
3. Functional failure analysis (FFA)
4. Critical item selection

5. Data collection and analysis
6. Failure modes, effects and criticality analysis (FMECA)
7. Selection of maintenance actions
8. Determination of maintenance intervals
9. Preventive maintenance comparison analysis
10. Treatment of non–critical items
11. Implementation
12. In–service data collection and updating

1.2.1 Study Preparation

The main objectives of an RCM analysis are:
1. To identify effective maintenance tasks,
2. To evaluate these tasks by some cost–benefit analysis, and
3. To prepare a plan for carrying out the identified maintenance tasks at optimal intervals.

If a maintenance program already exists, the result of an RCM analysis will often be to eliminate inefficient maintenance tasks.

1.2.2 System Selection and Definition

Before a decision to perform an RCM analysis at a plant is taken, two questions should be considered:

· To which systems are an RCM analysis beneficial compared with more maintenance that is traditional planning?

· At what level of assembly (plant, system, subsystem . . .) should the analysis be conducted?

Regarding the first question, all systems may in principle benefit from an RCM analysis. With limited resources, we must, however, usually make priorities, at least when introducing the RCM approach in a new plant. We should start with the systems that we assume will benefit most from the analysis. The following criteria may be used to prioritize systems for an RCM analysis:

(i) The failure effects of potential system failures must be significant in terms of safety, environmental consequences, production loss, or maintenance costs.
(ii) The system complexity must be above average.
(iii) Reliability data or operating experience from the actual system, or similar systems, should be available.

Most operating plants have developed an assembly hierarchy, i.e. an organization of the system hardware elements into a structure that looks like the root system of a tree. In the offshore oil and gas industry, this hierarchy is usually referred to as the tag number system.

1.2.3 Functionala Failure Analysis

The objectives of this step are:
(i) To identify and describe the systems's required functions,
(ii) To describe input interfaces required for the system to operate, and
(iii) To identify the ways in which the system might fail to function.

1.2.3.1 Identification of system functions

The objective of this step is to identify and describe all the required functions of the system. In many guidelines and textbooks, it is recommended that the various functions are expressed in the same way, as a statement comprising a verb plus a noun – for example, "close flow", "contain fluid", "transmit signal".

A complex system will usually have a high number of different functions. It is often difficult to identify all these functions without a checklist. The checklist or classification scheme of the various functions presented below may help the analyst in identifying the functions. The same scheme will be used in Step 6 to identify functions of analysis items. The term item is therefore used in the classification scheme to denote either a system or an analysis item.

1. *Essential functions:* These are the functions required to fulfill the intended purpose of the item. The essential functions are simply the reasons for installing the item. Often an essential function is reflected in the name of the item. An essential function of a pump is for example to pump a fluid.

2. *Auxiliary functions:* These are the functions that are required to support the essential functions. The auxiliary functions are usually less obvious than the essential functions, but may in many cases be as important as the

essential functions. Failure of an auxiliary function may in many cases be more critical than a failure of an essential function. An auxiliary function of a pump is for example containment of the fluid.

3. *Protective functions:* The functions intended to protect people, equipment and the environment from damage and injury. The protective functions may be classified according to what they protect, as:

· safety functions
· environment functions
· hygiene functions

An example of a protective function is the protection provided by a rupture disk on a pressure vessel (e.g. a separator).

4. *Information functions:* These functions comprise condition monitoring, various gauges and alarms etc.

5. *Interface functions:* These functions apply to the interfaces between the item in question and other items. The interfaces may be active or passive. A passive interface is for example present when an item is a support or a base for another item.

6. *Superfluous functions:*

"Items or components are sometimes encountered which are completely superfluous. This usually happens when equipment has been modified frequently over a period of years, or when new equipment has been over specified". Superfluous functions are sometimes present when the item has been designed for an operational context that is different from the actual operational context. In some cases failures of a superfluous function may cause failure of other functions.

For analysis purposes the various functions of an item may also be classified as:

(a) *On–line functions:* These are functions operated either continuously or so often that the user has current knowledge about their state. The termination of an on–line function is called an evident failure.

(b) *Off–line functions:* These are functions that are used intermittently or so infrequently that their availability is not known by the user without some special check or test. The protective functions are very often off–line functions. An example of an off–line function is the essential function of an emergency shutdown (ESD) system on an oil platform. Many of the protective functions are off-line functions. The termination of an off–line function is called a hidden failure. Note that this classification of functions should only be used as a checklist to ensure that all relevant functions are revealed. Discussions about whether a function should be classified as "essential" or "auxiliary" etc. should be avoided.

Also note that the classification of functions here is used at the system level. Later the same classification of functions is used in the failure modes, effects and criticality analysis (FMECA) in Step 6 at the analysis item level.

The system may in general have several operational modes (e.g. running, and standby), and several functions for each operating state.

The essential functions are often obvious and easy to establish, while the other functions may be rather difficult to reveal.

1.2.3.2 Functional block diagrams

The various system functions identified in Step1.2.3.1may be represented by functional diagrams of various types. The most common diagram is the so–called functional block diagram.

1.2.4 Critical Item Selection

The objective of this step is to identify the analysis items that are potentially critical with respect to the system failure modes (functional failures).These analysis items are denoted functional significant items (FSI). Note that some of the less critical system failure modes have been disregarded at this stage of the analysis. Further, the two failure modes "total loss of function" and "partial loss of function" will often be affected by the same items (FSIs). For simple systems the FSIs may be identified without any formal analysis. In many cases, it is obvious which analysis items that have influence on the system functions. For complex systems with an ample degree of redundancy or with buffers, we may need a formal approach to identify the functional significant items. This means that the causal analysis in the conceptual model should be pursued down to the analysis item level and not further. As explained in section 2, the basic events will also comprise events that are not classified as analysis item failures, like human errors and environmental impacts. In the conceptual model, fault tree analysis is suggested as a suitable technique for identification and modeling of basic events. Depending on the complexity of the system, other techniques like reliability block diagrams, may be more suitable. In an petroleum production plant there are often a variety of buffers and rerouting possibilities.

Rerouting will also be possible in railway applications. For such systems, Monte Carlo next event simulation may often be the only feasible approach. If failure rates and other necessary input data are available for the various analysis items, it is usually a straightforward task to calculate the relative importance of the various analysis items based on a fault tree model or a reliability block diagram. In a Monte Carlo model it is also rather straightforward to rank the various analysis items according to criticality. The main reason for performing this task is to screen out items that are more or less irrelevant for the main system functions, i.e. in order not to waste time and money analyzing irrelevant items.

In addition to the FSIs, we should also identify items with high failure rate, high repair costs, low maintainability, long lead time for spare parts, or items requiring external maintenance personnel. These analysis items are denoted maintenance cost significant items (MCSI). The sum of the functional significant items and the maintenance cost significant items are denoted maintenance significant items (MSI). Some authors, claim that such a screening of critical items should not be done, others claim that the selection of critical items is very important in order not to waste time and money. We tend to agree with both. In some cases it may be beneficial to focus on critical items, in other cases we should analyze all items. In the FMECA analysis of Step 6, each of the MSIs will be analyzed to identify their possible impact upon failure on the four consequence classes: (S) safety of personnel, (E) environmental impact, (A) production availability, and (C) Economic losses. This analysis is partly inductive and will focus on both local and system level effects. From the present step we know that a failure of an MSI may have impact on one or more of the system functions. In addition, the failure of an MSI may have several local effects and also effects on system level not involving the identified system functions. There may also be analysis items, that are not classified as MSIs, that have negative effects on the system level not involving the identified system functions. This observation may be seen as an argument for not to screen out so–called noncritical items.

1.2.5 Data Collection and Analysis

The data necessary for the RCM analysis may be categorized in the following three groups:

1.2.5.1. *Design data*

- System definition: a description of the system boundaries including all subsystems and equipment to fulfill the main functions of the system.
- System breakdown: the assembly hierarchy as described in Step 2.
- A technical description of each subsystem, such as the structure of the subsystem, capacity and functions (e.g. input and output).
- System performance requirements, e.g. desired system availability, environmental requirements.
- Requirements related to maintenance/testing e.g. according to rules and regulations.

1.2.5.2. *Operational data*

- Performance requirements
- Operating profile (continuous or intermittent operation)
- Control philosophy (remote/local and automatic/manual)
- Environmental conditions
- Maintainability
- Calendar– and accumulated operating time for overhauls
- Maintenance and downtime costs
- Recommended maintenance for each analysis item based on manufacturer specification, general guidelines or standards, or in–house recommended practice.

Failure information, when a failure occurs the following registrations are relevant:
- System number (tag number) of the analysis item
- Calendar time
- Accumulated operating time to the failure
- Failure event
- Failure mode
- Failure cause
- Failure consequences
- Repair time (active and passive)
- Downtime

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3. *Reliability data*

Reliability data may be derived from the operational data. The reliability data is used to decide the criticality, to mathematically describe the failure process and to optimize the time between PM–tasks. The reliability data includes:

- Mean time to failure (MTTF).
- Mean time to repair (MTTR).
- Failure rate function $z(t)$.

A functional relation between the value of condition monitoring information and the failure rate $z(t)$.

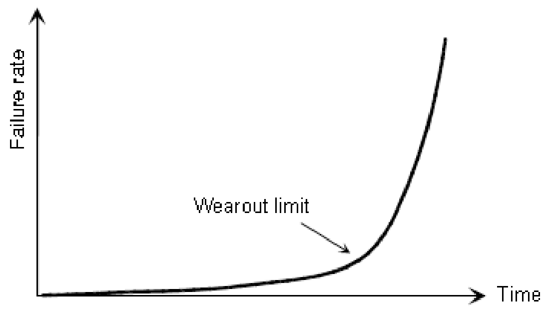

Fig. 1: Failure rate with identifiable wear out limit

1.2.6 Failure Modes, Effects and Criticality Analysis

The objective of this step is to identify the dominant failure modes of the MSIs identified during Step 4. A wide variety of different FMECA forms are used in the main RCM references. The various columns in this FMECA form are discussed below:

MSI: This will typically be the analysis item number in the assembly hierarchy (tag number), optionally with a descriptive text.

Operational mode: The MSI may have various operational modes, for example running and standby.

Function: For each operational mode, the MSI may have several functions. A function of a standby water supply pump is for example to start upon demand.

Failure mode: A failure mode is the manner by which a failure is observed, and is defined as non–fulfillment of one of the equipment functions.

Effect of failure/Severity class: The effect of a failure is described in terms of the “worst case” outcome with respect to safety (S), environmental impact (E), production availability (A), and direct economic cost (C).

The effect can either be specified by means of consequence classes, or some numerical severity measure. A failure of an MSI will not necessarily give a “worst case” outcome due to e.g. redundancy, buffer capacities, etc. A conditional likelihood field is therefore introduced. *“Worst case” probability:* The “worst case” probability is defined as the probability that an equipment failure will give the “worst case” outcome. To obtain a numerical probability measure, a system model is required. This will often be inappropriate at this stage of the analysis, and a descriptive measure may be used. Proposed classes are “serial”, “redundancy”, “cold standby”, “hot standby”, and “buffer”.

MTTF: Mean time to failure for each failure mode is recorded. Either a numerical measure or likelihood classes may be used.

Criticality: The criticality field is used to tag off the dominant failure mode according some criticality measure. A criticality measure should take failure effect, “worst case” probability and MTTF into account. “Yes” is used to tag off the dominant failure modes. The information described so far should be entered for all failure modes. A screening may now be appropriate, giving only dominant failure modes, i.e. items with high criticality.

For the dominant failure modes the following fields are required:

Failure cause: For each failure mode there may be several failure causes. An MSI failure mode will typically be caused by one or more component failures. Note that supporting equipment to the MSIs entered in the FMECA form is for the first time considered at this step. In this context a failure cause may therefore be a failure mode of a supporting equipment. A “fail to close” failure of a safety valve may for example be caused by a broken spring in the failsafe actuator.

Failure mechanism: For each failure cause, there is one or several failure mechanisms. Examples of failure mechanisms are fatigue, corrosion, and wear.
Percentage MTTF: The MTTF was entered on an MSI failure mode level. It is also relevant to enter the MTTF for each failure mechanism. To simplify, a percent is given, and MTTF can be calculated for each failure mechanism. The percentage MTTF will obviously be only an approximation since the failure mechanisms usually are interdependent.
Failure characteristic: Failure propagation may be divided into three classes.
1. The failure propagation can be measured by one or several (condition monitoring) indicators. The failure is referred to as a “gradual failure”.
2. The failure probability is age–dependent, i.e. there is a predictable wear out limit. The failure is referred to as an “ageing failure”.
3. Complete randomness. The failure cannot be predicted by either condition monitoring indicators or by measuring the age of the item. The time to failure can only be described by an exponential distribution, and the failure is referred to as a “sudden failure”.
Maintenance action: For each failure mechanism, an appropriate maintenance action may hopefully be found by the decision logic in Step 7. This field can thus not be completed until Step 7 is performed.

Failure characteristic measure: For “gradual failures”, the condition monitoring indicators are listed by name. ”Ageing failures are described by an ageing parameter, i.e. the “shape” parameter (a) in the Weibull distribution is recorded.
Recommended maintenance interval: The identified maintenance action is performed at intervals of fixed length. The length of the interval is found in Step 8.

1.2.7 Selection of Maintenance Action

This phase is the most novel compared to other maintenance planning techniques. A decision logic is used to guide the analyst through a question–and–answer process. The input to the RCM decision logic is the dominant failure modes from the FMECA in Step 6. The main idea is for each dominant failure mode to decide whether a preventive maintenance task is suitable, or it will be best to let the item deliberately run to failure and afterwards carry out a corrective maintenance task. There are generally three reasons for doing a preventive maintenance task:
(a) To prevent a failure
(b) To detect the onset of a failure
(c) To discover a hidden failure

Only the dominant failure modes are subjected to preventive maintenance. To obtain appropriate maintenance tasks, the failure causes or failure mechanisms should be considered. The idea of performing a maintenance task is to prevent a failure mechanism to cause a failure.

Hence, the failure mechanisms behind each of the dominant failure modes should be entered into the RCM decision logic to decide which of the following basic maintenance tasks that is applicable:
1. Continuous on–condition task (CCT)
2. Scheduled on–condition task (SCT)
3. Scheduled overhaul (SOH)
4. Scheduled replacement (SRP)
5. Scheduled function test (SFT)
6. Run to failure (RTF)

1.2.8 Determination of Maintenance Interval

The RCM decision logic was qualitatively used to establish preventive maintenance tasks. These tasks are performed at times kt, k=1,2, . . . , . Hence, for each task, the optimal interval t should be decided. When balancing costs, we realize that the preventive maintenance cost increases with decreasing t, and the cost of unplanned failures decreases with decreasing t. In this presentation, only tree simple models are discussed. Model one and Model 2 are appropriate models for scheduled rework/replacement task, while Model 3 may be used for scheduled function testing. For more general models. To determine the optimal interval t some crucial information is required. First we need information about cost structures, i.e. the total cost of the preventive maintenance action and the total cost of a failure which the maintenance action was supposed to prevent. Note that the models are developed for single unit systems, thus for redundant systems we realize that a failure needs not necessarily give a system failure. If the cost of a system failure is c_s, then the cost element to use in the model should be $cs= p + cr$ where p is the probability that the (redundant) unit will cause a system failure, and cr is the repair/replacement cost of the unit. In addition to cost structures, information about the actual failure distribution is necessary. This information will typically be mean time to failure (MTTF), and the shape parameter for units where ageing, wear, corrosion etc. are present. Note that the failure information should be obtained at a failure cause level, i.e. corresponding to the failure cause the preventive maintenance task is designed for.

1.2.9 Preventive Maintenance Comparison Analysis

Two overriding criteria for selecting maintenance tasks are used in RCM. Each task selected must meet two requirements:
· It must be applicable
· It must be effective

Applicability: Meaning that the task is applicable in relation to our reliability knowledge and in relation to the consequences of failure. If a task is found based on the preceding analysis, it should satisfy the Applicability criterion. A PM task will be applicable if it can eliminate a failure, or at least reduce the probability of occurrence to an acceptable level - or reduce the impact of failures!
Cost-effectiveness: meaning that the task does not cost more than the failure(s) it is going to prevent.
The PM task's effectiveness is a measure of how well it accomplishes that purpose and if it is worth doing. Clearly, when evaluating the effectiveness of a task, we are balancing the "cost" of "performing the maintenance with the cost of not performing it. In this context, we may refer to the cost as follows (Hoch 1990):
1. The "cost" of a PM task may include:
· The risk of maintenance personnel error, e.g. "maintenance introduced failures"
· The risk of increasing the effect of a failure of another component while the one is out of service
· The use and cost of physical resources
· The unavailability of physical resources elsewhere while in use on this task
· Production unavailability during maintenance
· Unavailability of protective functions during maintenance of these
· "The more maintenance you do the more risk you will expose your maintenance personnel to"
2. On the other hand, the "cost" of a failure may include:
· The consequences of the failure should it occur (i.e. loss of production, possible violation of laws or regulations, reduction in plant or personnel safety, or damage to other equipment)
· The consequences of not performing the PM task even if a failure does not occur (i.e., loss of warranty)
· increased premiums for emergency repairs (such as overtime, expediting costs, or high replacement power cost).

1.2.10 Treatment of Non-MSIs

In Step 4 critical items (MSIs) were selected for further analysis. A remaining question is what to do with the items which are not analyzed. For plants already, having a maintenance program it is reasonable to continue this program for the non-MSIs. If a maintenance program is not in effect, maintenance should be carried out according to vendor specifications if they exist, else no maintenance should be performed.

1.2.11 Implementation

A necessary basis for implementing the result of the RCM analysis is that the organizational and technical maintenance support functions are available. A major issue is therefore to ensure the availability of the maintenance support functions. The maintenance actions are typically grouped into maintenance packages, each package describing what to do, and when to do it.

As indicated in the outset of this paper, many accidents are related to maintenance work. When implementing a maintenance program it is therefore of vital importance to consider the risk associated with the execution of the maintenance work. Checklists could be used to identify potential risk involved with maintenance work:
· Can maintenance people be injured during the maintenance work?
· Is work permit required for execution of the maintenance work?
· Are means taken to avoid problems related to re-routing, by-passing etc.?
· Can failures be introduced during maintenance work? etc.
Task analysis, may be used to reveal the risk involved with each maintenance job for a further discussion on implementing the RCM analysis results.

1.2.12 In-service Data Collection and Updating

As mentioned earlier, the reliability data we have access to at the outset of the analysis may be scarce, or even second to none. In our opinion, one of the most significant advantages of RCM is that we systematically analyze and document the basis for our initial decisions, and, hence, can better utilize operating experience to adjust that decision as operating experience data is collected. The full benefit of RCM is therefore only achieved when operation and maintenance experience is fed back into the analysis process. The process of updating the analysis results is also important because nothing remain constant, best seen considering the following arguments:

· The system analysis process is not perfect and requires periodic adjustments.
· The plant itself is not a constant since design, equipment and operating procedures may change over time.
· Knowledge grows, both in terms of understanding how the plant equipment behaves and how technology can increase availability and reduce costs.

II. CONCLUSION

RCM is not a simple and straightforward way of optimizing maintenance, but ensures that one does not jump to conclusions before all the right questions are asked and answers given. RCM can in many respects be compared with Quality Assurance. By rephrasing the definition of QA, RCM can be defined *All systematic actions required to plan and verify that the efforts spent on preventive maintenance are applicable and cost-effective.*

Thus, RCM does not contain any basically new method. Rather, RCM is a more structured way of utilizing the best of several methods and disciplines. We see the RCM concept as a way to reduce this "isolation" by closing the gap between the traditionally more design related reliability methods, and the practical related operating and maintenance personnel.

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