Abstract

It is a well-known fact that investment in condition monitoring is an effective way of improving the overall efficiency of assets in industry. However, regardless of recent developments in detection and analysis methods, condition monitoring is even today relatively expensive because it is labour-intensive and requires expert resources. Therefore, it is of major interest to industries to be able to define an optimum maintenance strategy for each piece of equipment. In practice, industries are looking for methodology to minimise the number of assets to be monitored, without having to compromise on their financial interests.

Several effective methods have been developed for defining which are the assets that should be monitored and by what means. There are numerous documented cases in aviation and nuclear industry, for example, on how maintenance tasks, including condition monitoring, have been defined using risk analysis methods, Reliability-Centered Maintenance (RCM), etc. Even though all this is common knowledge and well documented, these processes are not common in typical process industry. The reason appears to be that most of the methods are very time-consuming and require special expertise, which entails high costs. Therefore, industry needs a relatively simple method for asset classification in order to focus on the right assets. The method has to provide reliable results and cover all critical machinery. In addition, it has to be simple so that it does not require extensive training or too much work. Furthermore, the method must have dynamic capabilities to ensure that changes can be incorporated.

This paper discusses the practical aspects that limit the possibilities of industry to systematically utilise sophisticated methods as the basis of preparing the maintenance strategy. The paper also gives an overview of the concept to classify machinery, including the criticality analysis of assets combined with well-known classification methodologies.
1. Introduction

The most efficient maintenance results in modern industrial maintenance are achieved through the combination of different equipment-level maintenance strategies, such as condition-based maintenance, preventive maintenance and run-to-failure (RTF) completed with a systematic continuous improvement process.

Several methodologies have been developed to systematically plan and execute maintenance and equipment level strategies. Concepts like Total Cost of Ownership (TCO), Life Cycle Assessment (LCA) and Overall Equipment Effectiveness (OEE) should be put in practice in order to improve the benefits of a smarter approach to product design and to safe equipment operation by taking into account maintenance capabilities (1).

The challenge in industry is how to define an optimum maintenance programme. There are several factors that should be taken into consideration when planning and setting up the maintenance and condition monitoring programme, though eventually the management will make decisions by comparing predicted costs with the financial benefits available through the improved reliability of assets.

The start-up cost elements in the Condition Based Maintenance (CBM) programme include the definition of the assets to be monitored, the costs of acquiring predictive maintenance tools and equipment, investment in training to acquire knowledge as well as costs for setting up the condition monitoring programme. Long-term costs include all the costs related to monitoring and analysis.

The benefits of condition monitoring can be understood and measured using the concept of Overall Equipment Effectiveness (OEE). Today this particular measure, which has been derived from Total Productive Maintenance (TPM) introduced in the late 1980’s (2), is widely used in the process industry (3).

The fundamental idea of OEE is to measure equipment losses shown as deviations from the ideal status. The losses are classified in terms of performance, speed and quality losses, and the benefit of proper maintenance is then the avoidance of these losses.

It is often easier to calculate cost savings, which can also be reached quite easily in some cases, even though the results may not be favourable in the long-term. According to Finnish statistics, the overall maintenance cost in industry is 5.6 percent of turnover and varies depending on the industrial branch (4). On the other hand, the OEE losses are on the average 25 to 35 percent in industry (4, 5). Therefore, it is easy to conclude that the focus in maintenance should be shifted from reducing costs to OEE improvements since there is a lot more to gain.
Although it is commonly known that a suitable maintenance programme is an excellent way of achieving significant efficiency improvements in industry, maintenance planning is rarely based on a systematic analysis. A typical excuse for this is that often the documented methods are considered too time consuming, complex and thus too expensive to apply. This is why there is a major need for a practical method for planning maintenance reliably and classifying which assets should be included in the condition monitoring programme.

2. Asset selection as part of the maintenance planning process

For a long time maintenance was carried out by employees themselves, with no defined parameters. Equipment maintenance was more loosely organised and there was no haste for making the machinery or tools operational again. Today the focus is on keeping the equipment operational or returning it to production as quickly as possible \(^3\). Maintenance planning should be a systematic process to define maintenance practices so that assets are performing optimally and maintenance resources are utilised optimally.

The origins of methods for planning and running maintenance operations are different but when studying their substance, it can be concluded that they are all quite similar. In short, the ultimate targets of modern maintenance can be simplified to the following two sentences.

1. Machinery failures are not allowed to disturb production or harm people or the environment.
2. It is not acceptable to repair machines that are not broken.

This may sound trivial but these two sentences describe all the targets that the maintenance organisation needs. The first one states that maintenance has to operate so that OEE losses will be minimised. The second one has two meanings. Firstly, it will save maintenance costs, as only the necessary tasks will be performed, and secondly, it will reduce the number of failures in order to avoid unnecessary maintenance actions. Accordingly, the means by which the above two targets are met can be simplified as:

1. Critical machinery should be maintained based on its actual condition.
2. Systematic preventive maintenance practices have to be planned for all assets.
3. For non-critical machinery, failures can be accepted.

If it is not possible to prevent production disturbances by the above means, there is probably a need to redesign the process or asset in question.

An industrial production facility is a combination of complex machinery that is needed for processing raw materials for the end product. The key target for maintenance
planning is to find where costs could be optimised. Maintenance has to provide the right value to the right optimisation goals, not always the maximum or minimum. An example of a generic list of possible maintenance optimization criteria has been drawn up and divided into five maintenance objective groups: maintenance costs, functional and technical aspects (availability, reliability, maintainability, OEE and maintenance quality), strategic decisions (capital replacement decisions and lifecycle optimization), support (inventory of spare parts and logistics) and people and the environment (environmental impact, safety/risk and personnel management) \(^{(6)}\).

To understand the benefits available through condition monitoring, it is necessary to consider several different aspects. The nature of the process, the value of production and the criticality of assets are among the most important factors. If the process runs 24/7 and the value of the production is high, it is quite evident that it is important to try to minimise potential production disturbances through condition monitoring, for example. The level of process integration, the level of production buffers and e.g. the use of duplex machinery are also important. On top of all this, risks related to personnel or the environment always have the overriding priority.

The planning and implementation of a Condition Based Maintenance CBM programme is one of the key tasks for accomplishing an optimum solution. For example, in RCM methodology the overriding priority is first to see if it is possible to detect failures by means of condition monitoring (on-condition tasks) \(^{(7)}\). If no such methods exist, then the secondary options are considered.

### 3. Typical methods for selecting assets for condition monitoring

In general, the maintenance planning processes are poorly documented in industry. Many industrial plants in Western Europe are rather old and the age of different parts of the same process can vary significantly. According to studies, the average age of industrial assets in Europe is close to twenty years \(^{(8)}\).

In many cases the condition monitoring practices in industry in Western Europe have first been set up in the 1980’s or 1990’s when modern condition monitoring systems entered the market. Even the CBM programmes of today are still usually based on these old practices. Therefore, maintenance planning, asset selection, measurement settings, analysis practices and other condition monitoring methods have developed slowly in industry. This means that advanced new technologies or signal processing methods, such as the use of higher order derivatives \(^{(9)}\) or more intelligent automatic diagnostic systems, have not been fully utilised.

In the early days a common method for selecting assets for condition monitoring was based on principles derived from expertise at the plant, complemented with the
recommendations of suppliers. The assets in the industrial process have often been purchased and their maintenance plans designed in the course of decades, which has led to inconsistent practices even within a single plant but especially between different plants.

The need to develop maintenance planning was already recognised by the plants for more than a decade ago, and industries have taken quite significant efforts to find a reasonable solution for more systematic planning for their condition monitoring practices. Some of the methods used in the planning of a maintenance and condition monitoring programme are shown in Table 1.

Table 1. Characteristics of maintenance planning procedures.

<table>
<thead>
<tr>
<th>Basis of maintenance programme</th>
<th>Positive aspects</th>
<th>Negative aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical experience at the plant</td>
<td>Good understanding of the actual production processes.</td>
<td>Often limited documentation.</td>
</tr>
<tr>
<td></td>
<td>Well known maintenance history.</td>
<td>Inconsistent practices.</td>
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<td></td>
<td></td>
<td>Variation at the level of practical experience.</td>
</tr>
<tr>
<td>Recommendations of machinery suppliers</td>
<td>Based on detailed know-how on machine design.</td>
<td>Oversized maintenance requirements for security reasons.</td>
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<td></td>
<td></td>
<td>Often lack of know-how of the actual process.</td>
</tr>
<tr>
<td>RCM and RCM-2 processes</td>
<td>A systematic documented process based on the functions of assets.</td>
<td>Often leads to complex projects.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Requires a lot of work.</td>
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<tr>
<td>Risk simulation methods</td>
<td>A systematic and exact method for evaluating asset criticalities.</td>
<td>Very complex and time consuming.</td>
</tr>
<tr>
<td></td>
<td>Easy to use also for simulating different options.</td>
<td>Requires significant special expertise.</td>
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<td></td>
<td>Suits well for the design phase.</td>
<td>Difficult to use for existing assets because of the lack of data.</td>
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4. Streamlined processes for maintenance planning

In the last decade, it has become evident that the selection of assets for condition monitoring has to be integrated with maintenance planning. There have been approaches where the need for condition monitoring was evaluated as a separate process \(^{10}\). This may be a viable option if it is not possible for practical reasons to perform more complex maintenance planning.
In order to be efficient, the maintenance planning process has to be systematic and provide information for selecting the most efficient maintenance strategy for each individual piece of equipment. The other limiting factor is economy, which means that the price tag of maintenance planning and the implementation of the plan must be in balance with the benefits of these functions.

The aim of the today’s planning systems is to combine the benefits of different methods that were listed in Table 1. In industry, the methods where the RCM is used as the basis have recently become the dominating maintenance planning system.

The original RCM and RCM-2 processes have been widely in use in the aircraft industry and in some other industries where reliability is very critical, such as the nuclear power industry. These processes have also proved to be useful for some equipment manufacturers. Thanks to the above successes, there have also been numerous attempts to utilise the processes in the process industry. However, most of the attempts have not been successful, due to the complexity of the method, which requires special expertise and is very time-consuming, i.e. the method generates a lot of costs. Therefore, it can be said that RCM as such is not applicable to maintenance planning in typical process industry even though it has been originally designed for maintenance planning.

The basic idea of RCM can still be applied in industry, but in order to be viable, the process has to be simplified. To simplify the maintenance planning process, the following guidelines should be followed:
- The RCM process has to be simplified in order to be able to efficiently analyse and plan maintenance actions.
- There has to be a direct connection to the financial requirements of the company.
- The expertise of the enterprise has to be used as efficiently as possible.
- The resulting plan has to be as simple as possible.
- The system has to be flexible in order to suit different types of industries.
- The system should be as dynamic as possible in relation to unexpected external turbulence.

4.1 Streamlined RCM

Figure 1 illustrates the Streamlined RCM process (SRCM) that is used by SKF. The process is based on the RCM-2 methodology but with some modifications. In this model, the assets or components that will be classified as critical will go through the task definition process according to RCM methodology. The streamlined path will be used for non-critical assets that will be processed using a more simple Run-to-Failure evaluation.
4.2 Criticality-Streamlined RCM

The SRCM process discussed above may still prove too complex or time-consuming in some cases. The process can be simplified even further by performing a separate asset criticality assessment before FMEA. Processes of this kind have become rather common in industry in the last decade. The streamlined RCM process with criticality assessment is illustrated in Figure 2.

In this process, a relatively simple asset criticality assessment will be performed at an early stage in the planning process. It is very important that the result of the criticality assessment is correct, since the assets or components that will be classified as non-critical will not be analysed in detail later in the process. This means that failure to detect critical assets may lead to major production problems. Regardless of this risk, the method has become very popular because it is a much faster and hence much more cost effective way of introducing the systematic approach to maintenance even if it means taking a risk. For industries, the application of the method still means a major improvement compared to the status of the majority of plants today.
4.3 Asset criticality assessment

The criticality assessment function of the maintenance planning process illustrated in Figure 2 has become increasingly common in industry. The actual practices to perform the criticality assessment vary considerably and there are no commonly accepted international procedures. The aim of the criticality assessment is to simplify the asset evaluation process and thereby decrease the costs of determining the maintenance programme.

Criticality is a characteristic of an item, describing the magnitude of the risk associated with the item. Criticality assessment is a process used to determine the level of criticality of assets, usually expressed by an index. The item is critical if the associated risk (injury to persons, significant material damage, production losses or other unacceptable consequences) cannot be considered acceptable.

Based on the index value, the assets are normally divided into different criticality categories according to their significance. There are usually three categories. The most critical assets will be subjected to a more detailed analysis procedure and less critical
assets can be processed using more simple procedures. The setting of category limits is usually based on practical experience at the plant.

Criticality assessment practices vary considerably and different service suppliers, for example, have developed their own methods and templates for it. A national standard (11) is in use in Finland, which describes the criticality classification process. According to the standard, the criticality index K can be calculated according to the following formula:

\[ K = p \left( W_s M_s + W_e M_e + W_p M_p + W_q M_q + W_r M_r \right) \]  

where

- \( p \) is the probability of failure,
- \( W \) is the weighting factor and
- \( M \) is the multiplier.

The subscripts \( s, e, p, q, r \) represent safety, environment, production, quality and repair.

In the criticality assessment process a team of professionals will go through all the assets within the defined boundaries and assign multipliers to each of the assets on safety risks, environmental risks, production losses, quality costs and repair or consequential costs. The weighting factors remain the same for all the assets in question but if needed they can be adjusted according to the special characteristics of the process before the analysis. The probability of failure can often be estimated through predicted mean time between failures. This method has been used successfully in different industries e.g. in combination with the risk matrix.

5. Conclusion

Maintenance programmes in industry are often outdated and based on experience or suppliers’ recommendations rather than systematic planning processes. This often leads to the lack of performance of maintenance function and decreases the overall efficiency of the industrial process.

There are several systematic maintenance planning procedures that have already been used successfully for decades. However, they have not become common in the process industry because of their complexity and application costs.

Simplified processes have been developed in the last decade in order to address the needs of industries to develop their maintenance practices. These systems utilise the best practices of risk analyses, RCM, FMEA etc. but are more cost-effective to use than the original procedures.

Approaches to simplify the processes originate from the idea that a more simple process should be employed for non-critical assets. The criticality assessment procedure for pre-
classifying the assets has proved to be an effective way of optimising the maintenance planning procedure.

The criticality assessment of an existing plant provides a lot of data for improvements in maintenance and in condition monitoring. However, the assessment usually takes the form of a project rather than a systematic process, so it will only be valid for as long as there are no major changes related to assets or industrial process. In the future, the focus should be on developing criticality assessment as an integral part of the maintenance programme and as a much more dynamic tool for continuous improvement.

Operators will play a more prominent role in machinery checks. The second future development goal should be to integrate important data with condition monitoring. Operator checks should already be defined early in the maintenance planning process.

The third future development goal should be to integrate other measurement data with maintenance data to support maintenance planning and implementation. It has been evident for decades that process data, for example, could provide valuable information to maintenance and vice versa, but the data are seldom exchanged. This is also true for other interesting data items, such as stress accumulation. The current maintenance planning methods are not well suited for utilising such data.

Today there are no commonly accepted practices for streamlined maintenance planning processes or criticality assessment. This means that it is practically impossible to compare results. Therefore, the fourth development goal should be to standardise these processes.

References