LEAN SMART MAINTENANCE – EFFICIENT AND EFFECTIVE ASSET MANAGEMENT FOR SMART FACTORIES

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Abstract

Maintenance is a key enabler for the smart factory. However, it is not sufficiently prepared for the demands of Industry 4.0. For an efficient and effective asset management maintenance processes and strategies need to be optimized and aligned according to these requirements. Knowledge and data management as well as the associated possibilities for predictive maintenance need to be focused. This paper introduces a model that enables resource and risk optimized lean smart maintenance. By combining lean management tools, risk analysis and data analytics the model supports the transition to an Industry 4.0 oriented asset management.

Keywords: smart maintenance, lean management, industry 4.0, risk based maintenance, smart factory

1. INTRODUCTION

Companies must perform highly flexible and agile in a dynamic environment. One of the key success factors in such an environment is a life cycle oriented and sustainable asset management. As maintenance is a main part of asset management, it needs to be focused.

Maintenance management must change towards the requirements of Industry 4.0 to become an enabler of the smart factory. Therefore, new concepts need to be developed. [1] The Lean Smart Maintenance (LSM) approach – combining lean philosophy and smart maintenance – meets these requirements [2].

This article introduces the new LSM concept and its application in a steel rolling mill. The implementation process of LSM and main results of the use case are shown.

2. LEAN SMART MAINTENANCE APPROACH

The LSM approach is a sophisticated maintenance concept, which is characterized thru a lean and learning orientation as well as a risk and resource oriented alignment. The objective is to improve efficiency and effectiveness of asset management. Figure 1 shows the development of maintenance management concepts. From break down maintenance – less value-creation and process orientation – towards Lean Smart Maintenance – high value-creation and process orientation.

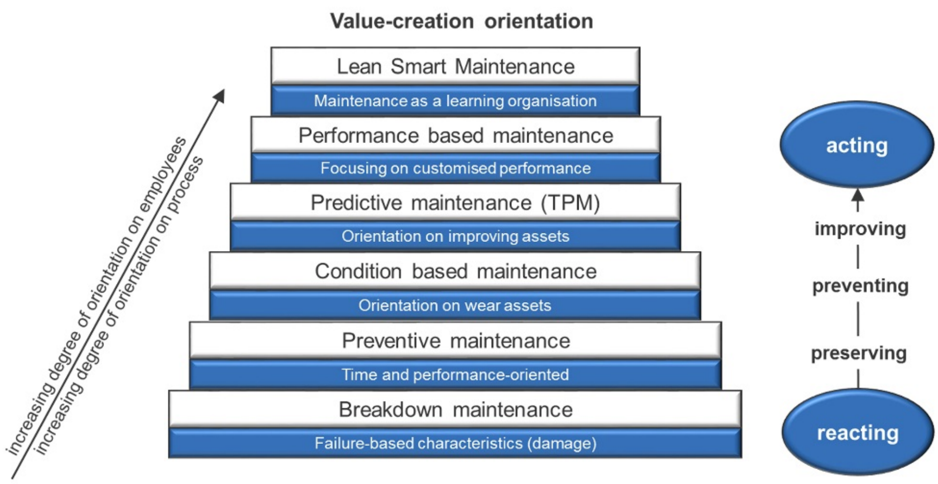

Figure 1 – Maintenance Management Concepts [3]

2.1 Smart Maintenance

The smart part represents the effectiveness perspective of the LSM approach. Smart Maintenance stands for an intelligent and learning maintenance management focussing on permanent improvement. The classic input control, which is cost oriented, is replaced by an output control, oriented on reliability, availability, maintainability and safety (RAMS) [2]. Important factors of smart maintenance are as follows:

- Data management

Increasing data availability opens huge potential for maintenance. To benefit from this potential a sophisticated data management is necessary. The right data enables e.g. predictive maintenance, weak-point reduction and maintenance strategy optimization. It also allows maintenance management to outline the contribution to a sustainable companyies success.

- Knowledge management

The evolution towards Industry 4.0 changes the scope of tasks for the maintenance staff. In addition, demographic change and lack of professional workers drastically increases the need for knowledge management. It is important to find ways to externalize and safe the knowledge of experienced employees and to provide it to new ones.

- Maintenance staff qualification

The Maintenance staff need to be prepared for smart maintenance. Therefor technological, methodical and organisational training is required. Staff qualification will play a key role in the development towards smart maintenance.

- Maintenance strategy optimisation

An asset specific strategy is important for an effective maintenance management. Hence, all available strategies – reactive, preventive, predictive and proactive – should be taken into consideration. As a production environment is a dynamic system maintenance strategy has to be adopted to new conditions. Therefore, the strategy selection process should be integrated into the maintenance control loop.

2.2 Lean Maintenance

The lean part is the efficiency perspective of the LSM approach. The philosophy is loss reduction on the input side of maintenance management systems. Resource conservation underlines the sustainable orientation of the LSM approach. The following factors are focused in the lean perspective: [2]

- Maintenance processes

By analysing maintenance processes, non-value adding activities are identified. In maintenance this are activities which do not contribute to a higher reliability or availability. Such activities should be reduced to a minimum. Key performance indicators as part of a customized maintenance scorecard support maintenance process optimization.

- Maintenance planning

Real-time maintenance planning is enabled thru better data availability in smart maintenance. This allows minimal reaction times on changing conditions. It also supports a dynamic maintenance order prioritization according to current requirements in the production.

- Management of external service

Another efficiency key factor for an optimal lean maintenance management is outsourcing. Make or buy decisions in coordination with maintenance strategy, management of external services, design of service level agreements and knowledge management need to be taken into consideration.

- Spare parts management

An assessment helps to identify critical spare parts. It builds the foundation of an efficient and lean spare parts management strategy. Models for breakdown predictions contribute to reduced storage costs.

- Weak-point analysis

Data analytics and modern computerized maintenance management systems (CMMS) support a sustainable weak-point reduction. Repeated repair work on the same objects is regarded as waste and should be avoided.

3. LEAN SMART MAINTENANCE IN THE STEEL INDUSTRY

The introduced LSM approach was applied in a use case in the steel industry. A steel mill is characterized by the high value of the installed assets, high failure costs due to a chained manufacturing system and high flexibility demands. This requires an efficient and effective maintenance management. In the use case the maintenance management of a steel rolling mill, with its upstream and downstream equipment, from the oven to the warehouse, was optimized.

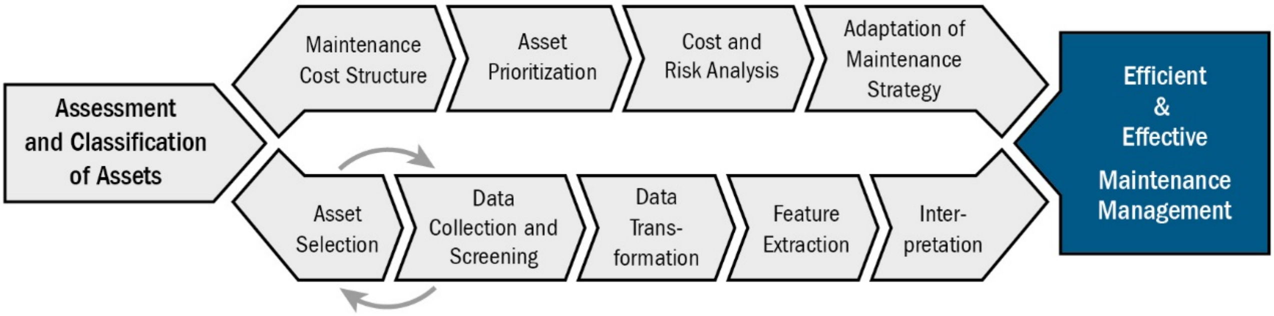

Figure 2 – *LSM Process Model*

Figure 2 shows the LSM process model applied in the use case.

3.1 Asset Assessment and Classification

In the first step of the LSM process model all assets need to be assessed. With a structured assessment tool critical assets of a production system could be identified. This is an important step in the maintenance strategy finding process and helps to concentrate limited resources on critical assets.

The assessment should be done with a team of maintenance and operation experts from the shop floor, who have experience with the assets. Documentation during these workshops supports knowledge management in maintenance according to the smart path of LSM.

Depending on the companies requirements a few possible assessment tools are available. For a comprehensive risk orientation a classic risk assessment method is recommended. To consider different risk and cost oriented perspectives a criteria assessment tool should be used. [4]

Classification of the result is necessary, especially if there are many assets. In this use case a risk clustering method was applied.

3.1.1 Risk Assessment

With an adapted risk assessment the rolling mill and its upstream and downstream equipment was assessed. The classical attributes occurrence and extend of damage were supplemented by the probability of detection. Like in a FMEA, the multiplication of these three perspectives leads to the risk priority number (RPN). The risk with the highest RPN represents the criticality of an asset and gives a first ranking of the assets.

At first the attributes need to be defined. Therefor they were divided into six gradations (one to six), so that the RPN range was between one and 216. An occurrence of one represents risks that occur only once in more than twenty years. Whereas an occurrence of six means the risk occurs at least two times a year. A probability of detection of one means the risk is detected with a very high likelihood, before a damage occurs. A probability of detection of six stands for a risk that could not be detected before it occurs. The extent of damage represents the costs of the risk, from one very low to six very high (existential threat). It contains the failure costs (direct and indirect), spare part costs, contractual penalties, reject costs and other costs.

In assessment workshops with maintenance and operation experts, every asset and all potential risks were assessed. It is important to define a certain asset layer for the assessment. In a rolling mill, with its complex equipment, it would be too superficial to assess on the top layer of an asset. Nevertheless, it would also be much to detailed to assess on the component layer. However, the right degree of detail need to be fixed and used for all assets to obtain a comparable result. For a complete risk identification, potential risks should be listed from the experts in advance. Failure lists, experience knowhow of the staff and other available sources can be used.

A structured identification and assessment process also helps to identify risks, which have not been recognized yet. Documentation of the assessment results contributes to knowledge management in maintenance.

3.1.2 Clustering of risks

At the end of the risk classification, nearly 3000 different risks have been identified. To get a better look at the distribution of the risks in their entirety a clustering algorithm was used to aggregate risks to groups as uniform as possible. The procedure was realized in MATLAB® because it uses a wide range of implemented clustering algorithms. In this particularly case the k-means algorithm [5] was used to perform the clustering of the risks. The cluster attributes were the occurrence, the probability of detection and the extent of damage. As mentioned in chapter 3.1.1 these are the three dimensions of the risk assessment. Each of which was divided in six classes. Since the extent of damage is also available with an absolute value in Euros, it was decided to use it as cluster attribute instead of the six classes. Therefore, it is possible to weight the attribute "extent of damage" higher in relation to the other two attributes.

Since the k-means algorithm uses a fixed number of clusters, predetermined by the user, the program used a range of clusters. Then it determines a solution for each number of clusters and stores them for later evaluation. The cluster range was set between 5 and 20. To use less clusters would lead to the fact, that the risks in each one are not homogenous enough. Since it might be necessary to prioritize or derive strategies for the clusters, more than 20 deemed impractical.

Regularly the k-means algorithm in MATLAB® determines the cluster centroid seeds by applying the k-means++ algorithm [6]. Nevertheless, the cluster result was always better using the sample function, which randomly chooses the cluster centroid seeds. The quality of the result was determined by comparing the within-cluster sums of point-to-centroid distances. To avoid local minima it is good practice to set the replicates option in MATLAB®. By doing so, the program starts the clustering several times with different cluster centroid seeds. The number of replicates determines the number of cycles. The best result is once again determined by the minimum of the within cluster sums of point-to-centroid distances.

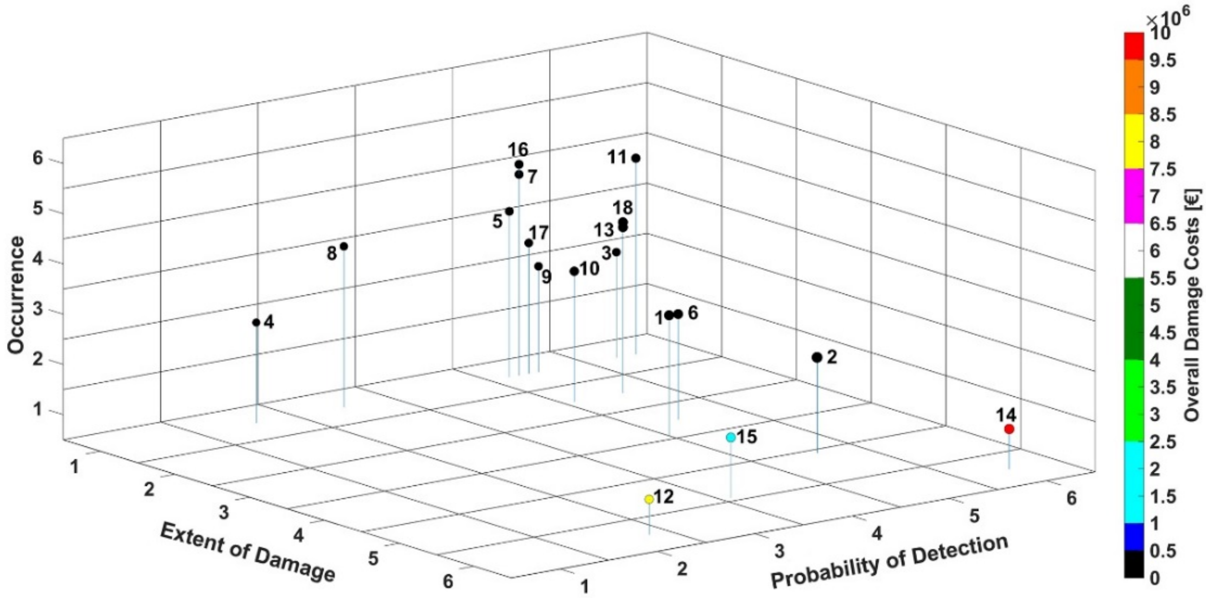

Figure 3 – Risk Clusters

Figure 3 shows the result of the risk clustering. The best number of clusters from the range between 5 to 20 was eighteen. Each cluster represents at least two risks. The numbering is arbitrary and determined by the program. The different colouring of the bubbles depicts the average overall damage costs of the risks in the given cluster. In the given case, most of the risks are not, or just on average critical. Only the risks in the clusters 14 and 12 are categorized highly critical. Those in cluster 15 are borderline to highly critical. Still all risks in the 3 mentioned clusters represent less than 1% of the identified risks. Looking at the different clusters it can be seen, that similar risks are grouped together. It is now possible to prioritize the clusters and start to assess the risks and implement measures to remove or minimize the risks. For example, the risks in cluster 16 can be seen as low hanging fruits. By increasing the number of inspection cycles or the implementation of condition monitoring, both, the occurrence of the risk and the probability of detection can be improved. Chapter 3.2 describes a structured approach for this.

3.1.3 Criteria Assessment

A risk assessment is a very time consuming process. That’s why a criteria assessment tool was developed. Less important objects were assessed with this tool.

An asset assessment tool should be customized according to the companies’ requirements. Therefor a team of maintenance and operation experts identify characteristic indicators. Figure 4 shows a criteria assessment tool with seven different indicators. Each indicator has three to five gradations. To get a comparable result, it is important to define the gradation qualitative or quantitative.

Object 1						Value	Asset index
availability	low	**medium**	high			3	15
susceptibility to failure	**low**	medium	high			1	
number of redundant assets	> 3	3	**2**	1	0	3	
maintenance costs	low	**medium**	high	very high		2	
age	young	**medium**	old			3	
influence on quality	none	**low**	medium	high		2	
downtime costs	**low**	medium	high			1	

Figure 4 – Criteria Assessment Tool

For example object 1 in figure 4 has a medium availability. This could be an availability between 60 % and 80 %, depending on the fixed boundaries for the gradations. Each gradation has a certain value. The sum of these values builds the asset index and is comparable to the RPN.

3.2 Lean Path

The lean path of the LSM process model (Figure 2) represents the input perspective of a maintenance management system [2]. In the first step, the maintenance costs and structure of the observed period need to be gathered and documented. This must be done at the same asset layer as the risk assessment. The costs should be divided into reactive and preventive costs as well as into labour, spare parts and external service costs.

The RPN from the risk assessment and the maintenance costs constitute the two dimensions of an asset prioritization diagram (Figure 5). The highest occurring RPN limits the x-axis and the highest maintenance costs limit the y-axis. Assets with a balanced ratio between risk and costs are within the highlighted diagonal line. Assets below or above this line should be investigated concerning over- or undermaintenance. This is done in the next step of the LSM process model. By analysing the costs and risks of the asset, reasons for an unbalanced ratio could be identified.

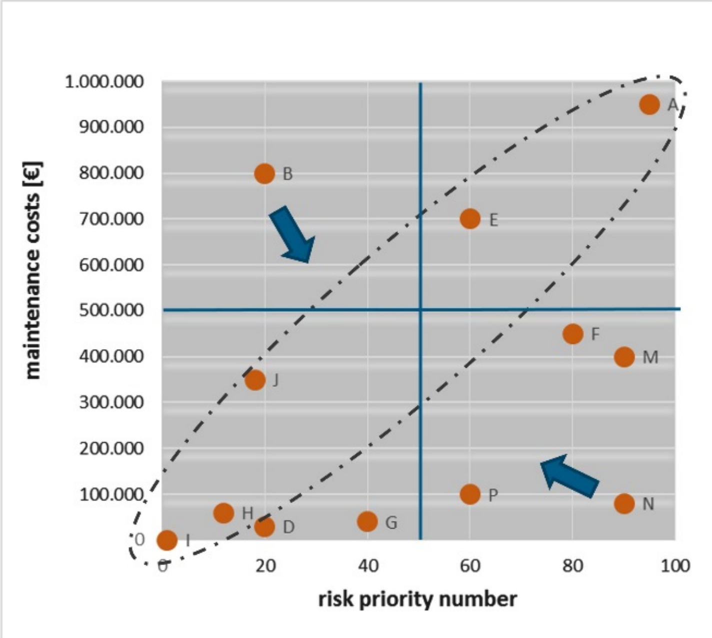

Figure 5 – Asset prioritization diagram

For example, asset B in Figure 5 has high maintenance costs and a low RPN – suspected overmaintenance. The maintenance costs should be analysed. Expensive preventive maintenance tasks could be changed or replaced by reactive strategies. For example extension of inspection intervals. It is important to consider the higher risks resulting thru these strategy adaptations. They must be acceptable. Otherwise the strategy should not be changed.

Asset N in Figure 5 has the opposite ratio between RPN and maintenance costs – suspected undermaintenance. In this situation the identified risks should be analysed. Suitable measures to reduce the high risks need to be found. This could be a constructive improvement, a preventive strategy or the installation of a condition monitoring system to improve the probability of detection.

Assets like A in Figure 5 with a high RPN and high maintenance costs should also be analysed. It must be checked if the cost intensive maintenance activities sufficiently contribute to a risk reduction.

The last step in the lean path of the LSM process model is the adaptation of maintenance strategy. Possible new strategies should be compared concerning the new risks and new maintenance costs. A documented and structured approach is recommended.

3.3 Smart Path

The smart path of the LSM Model uses data analytics in combination with the different data from sources like the production program, quality control, condition monitoring and the recordings from maintenance activities. It should allow a predictive maintenance strategy by building a prognosis model for breakdowns.

The asset selection uses the result of the previous assessment and classification step. In structured workshops one or more assets are being chosen, which will be considered for predictive maintenance. Roughly two types of assets may be suitable. On the one hand those with potentially high failure costs, which can be proactively prevented by the means of prognosis. On the other hand assets with frequent breakdowns, which will sum up to a high downtime. The later ones are even more preferred, because they cause a higher number of maintenance recordings, which is important to train a prognosis model. This leads to the main objective of a predictive strategy - the prognosis of breakdowns by means of collected data. In conclusion, it is imperative, that the data quality meets the requirements of a reliable prognosis. Data from diversified sources increases the possibility for finding relevant clues to predict breakdowns. The collection and screening of the different data is the next step in the smart path of the LSM model. If the data is not feasible to build upon a data-mining model, it might be necessary to increase the quality of the data or to return to the previous step and chose a different asset. That loop is quite typical for industrial applications of data analytics and is quite similar to the KDID-process [7].

The next part of the data collection and screening requires the inclusion of experts on the chosen asset. They need to identify relevant sequences in the data, which might contain relevant information for the prognosis model. The exclusion of non-relevant sequences may help to increase the prognosis performance because otherwise they might distort the result and lead to a miss interpretation.

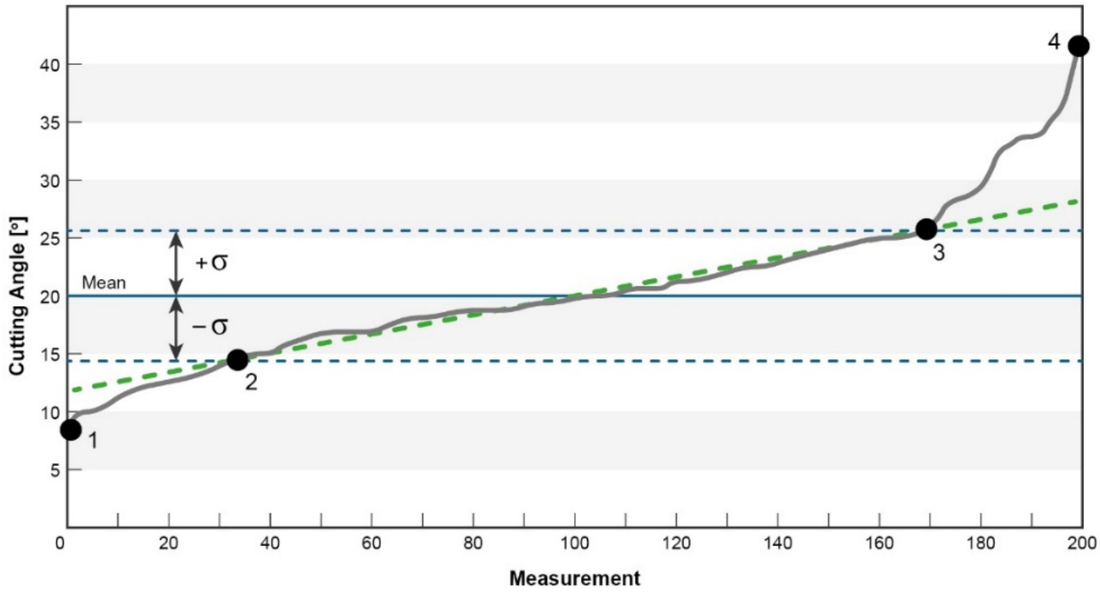

Figure 6 – Cutting Angle Trend

The third step envelops all procedures to transform the sensor signal to be clearly distinguishable from others. In this case, the AMT method [8] is applied, which allows expressing the complexity of a signal in few characteristic factors. These factors are used for the feature extraction in the next step of the smart path in the LSM model. By mapping the features over time and bringing them in relation to the maintenance activities, it is possible to make predictions about breakdowns [9].

Figure 6 depicts the characteristic cutting angle of a signal, extracted after the AMT transformation. Between points 2 and 3 a nearly linear trend, which indicates the area of normal operation is visible. The curve between points 3 and 4 indicates that the monitored component reaches a point near breakdown. The other side of the curve between 1 and 2 defines the area after a maintenance procedure, where the component levels off to normal operation conditions.

That knowledge can be used for the last step in which the results are interpreted and used to adapt the maintenance strategy towards a predictive approach in the spirit of Lean Smart Maintenance.

4. CONCLUSION

LSM combines the economic principles of an efficient input and output oriented asset management with a learning and knowledge based approach. It supports maintenance management to outline the contribution to a sustainable company’s success. An efficient and effective asset management as a main objective can be achieved. LSM supports maintenance management in its evolution towards smart maintenance and enables the change to a smart factory.

In the use case numerous efficiency and effectiveness potentials were pointed out. The risk assessment provided an important basis for strategic asset management decisions. Adaptation of maintenance strategy – lean path – reduced numerous of risks with low investments. Findings in the smart path helped to develop a successfully installed breakdown prognostic model.

5. REFERENCES

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