A Model to Describe the Relationships
Man–Machine–Maintenance–Economy (MMME)

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Abstract—In the globalisation spirit, one of the major objectives of companies is how to reduce the production losses cost-effectively for continuously enhancement of competitiveness and profitability. However, this area has been neglected by scientists and not given the attention justified considering its obvious link to company profitability. To fill this gap, better understanding of the relations and interactions between man, machine/production process, maintenance and economy is vital. Also, it is important for identifying and eliminating root causes of the losses. In this paper, we develop a model to describe these interactions using the most relevant factors, such as maintenance organisation, personnel commitment, machine condition and characteristics, and the impact of maintenance performance on production time. The use of the model and its potential benefits are tested using an application example. This example illustrates how the above mentioned factors affect the production time and is thereafter derived to financial results. The result is accordingly a model that can help all producing companies categorise the causes behind losses and identify where losses arise and where to focus their work of continuous cost-effective improvements.

Index Terms—Man–Machine–Maintenance–Economy Model, Maintenance impact on company’s business

I. INTRODUCTION

Today's business is characterized by an increasing globalization and competitiveness, which put huge pressure on all market actors. To survive, companies have to offer superior customer value, operate with lowest relative cost or preferably do both [4]. Maintenance is wrongly often regarded as a cost centre, since the costs are visible while the benefits can be difficult to estimate [3]. In [7], a case study is performed where the results show that the overall equipment effectiveness (OEE) was as low as 55%. Maintenance is a factor that affects OEE to a high extent and small investments in maintenance to enhance its performance can lead to appreciable reduction in production cost. Reduced production cost could lead to equivalent reduction of the product price, increased customer value and enhanced company competitiveness. A reduction in production cost can also lead to increased profit margin of the products and therefore increase the company profitability given that the price is not reduced and the production is sold. The problem addressed in this paper is; How to identify and classify problem areas in producing systems and thereby quantify generated losses for prioritising maintenance actions cost-effectively?

This paper focuses on categories of factors influencing machine/production process performance in addition to the benefits that can be achieved by maintenance and how these benefits can be transferred to the company’s strategic level. Machine in this case does not only mean the hard definition of a machine, but it can be replaced by e.g. the production process. Integrating maintenance in company’s strategic level is rather important to legalise maintenance as a strategic tool for fulfilling company’s objectives and accordingly helps to highlight maintenance role in the companies’ business [5]. The study takes into account how human resources and organization, machine/production process characteristics and maintenance policy affects the production time and, consequently, the company profit and business. In this paper, we develop a model that describes the interactions concerning Man–Machine–Maintenance–Economy (MMME). The model describes the interactions between the major actors or elements involved in production. It takes into account human resources and their interface with production process and machine. The model also handles the policy required for maintaining the product quality and machine performance, and the impact of all these factors on the company’s economy and profitability.

The model can be used to identify and classify the causes behind losses and assess their impact on the production time in all kinds of producing companies, i.e. goods producer or a service provider, even though it is most suited for the former. However, it can easily be adjusted, extended or curtailed in order to fit the company’s specific needs. Other features that have been considered in the model are that it should be transparent, user friendly and easy to understand by the personnel. In section II, the model is developed and described with respect to its contents, purpose and importance. In section III, an application example is conducted to illustrate the model use and its potential benefits followed by IV, discussion and conclusions.

II. A MODEL TO DESCRIBE THE RELATIONSHIP
MAN-MACHINE-MANAGEMENT-ECONOMY

According to our knowledge and the survey that have been done, there is lack of researches and publications highlighting
maintenance impact on company’s business. Reference [3] demonstrated that there are two main causes behind that:

(i) In general, maintenance has been regarded as a cost centre.
(ii) With respect to the available techniques, it demands big efforts to identify, quantify and follow up maintenance impact on company’s business because of its interactions with other working areas, e.g. production, quality, competence, operating environment and LCC management.

Generally, only costs are acknowledged to be derived from maintenance, while improvements that have been brought by more effective maintenance performance are usually credited financially to other working areas, such as production/operation, quality, life cycle cost, working environment, etc. For instance, a stable production process with negligible number of failures and a production speed with a very narrow variation limit will lead to delivery on time, which is one of the major strategic objectives of companies. Another example could be that fewer failures and shortened repair time (which is equivalent to prolonged production time) increase production quantities and enlarge profit margin which results in increased profit (given that all the production is sold), but the maintenance cost can also be increased [3]. In this case, it is necessary to compare the increment in maintenance cost with that in the production of high quality items in order to judge the cost-effectiveness of applying more efficient maintenance.

Another reason for developing the model is that in order to justify investments in maintenance, the economic aspects need to be clarified for the company board. If the board are going to invest the company’s money, they want to see the consequences of the investment in financial terms. In other words, they will not invest in projects that will not payback [6].

A. Model development

There are several disciplines in a company that interact with each other and affect the outcome (product), such as operation, human resources, quality, maintenance, production logistics, etc. However, the model is developed with respect to a broader maintenance perspective described by Total quality maintenance (TQMain), which focuses on maintaining the quality of all essential working areas involved in a production process such as human resources (and organization), quality, production logistics, working environment, maintenance policy and business (economy), not only machines [1,3]. It can be used to control the impact of investments in maintenance, and see whether it was cost-effective or not.

In addition, the model helps to identify problem areas causing production losses and the total change in technical and financial terms. The latter can be utilized as a trigger for starting deeper analysis to justify the solutions suggested when the losses can be assessed [3]. For simplicity, we neglect some variables (elements) that might have marginal effect on the number of failures and production time, such as quality of the raw material, condition of the machine tools, etc. The development of the model will be described in two stages; first the classification of the causes behind losses and second the elements of theses classes.

A classification of causes at the operative level is necessary to easily identify the losses in production time and consequently to analyse and distinguish the root causes behind them. Therefore, the model is divided into different segments to make it possible to highlight the causes of unplanned stoppages and production time loss. The operational level is divided into three main categories; human resources & organization, production process, and maintenance.

In the strategic level, we translate the technical data from the operative level into financial data. To gather the data needed, a certain amount of resources are required depending on how much data that is available and already collected at the company. It also depends on how the data are organised, i.e. if the databases are computerised or saved in manual registers. A schematic illustration of the classification of causes of failures and the prioritized area of improvement is shown in Fig. 1.

![Classification of the causes of production time loss](image)

Each category consists of several key elements that potentially could cause loss of production time. Each key element of the production time loss categories on the operative level will be described below, followed by the key elements of the strategic level. The mechanisms of transferring the impact of improvements in (or lack of or inefficient) maintenance to the plant other activities are quantitatively illustrated in Fig.2. Note that for easiness the lateral interactions between these elements are not considered in this paper. The model emphasises on the differences between measurements from previous and current period in order to ease identification and classification of problem areas and quantify the losses.

B. Human resources and organisation

One of the important resources required for production is human resources and organisation. These resources are as much as necessary also a source of problems that may cause losses in production time, such as the case of operator or maintenance technician unavailability when they are needed, insufficient training, lack of experience and commitment. The organisation as a foundation required for managing all these resources toward company’s strategic objectives is not always reliable in meeting the requirements of the enterprises. This is why some of the failures have their root-causes in these resources. The environment of a production line/station can be described using environment related parameters, such as ambient temperature, pressure, humidity, noise, vibration, pollution, dirt, etc. The working environment that is
surrounding the human resources and the organisation influences many attributes that affect the production time, such as health of the personnel, their working moral, condition and failure rates of the assets and buildings, the repair time needed to restore equipment, etc. Maintaining the quality of the working environment described by the value-levels of the attributes would increase the probability of eliminating the causes behind disturbances and production time losses. For example to reduce the probability of unavailability of personnel, enhance working moral, reduce deterioration rate of assets, etc. This is why TQM main and total productive maintenance promotes the need of a clean and well organized working environment [1,3,8]. When a failure occurs, it is important to know how to handle it and restore the machine to its previous condition as soon as possible without waiting times (which results in more production time losses). Routines and clear instructions are necessary to be established in order to make it easy for personnel to know what actions to take in different situations.

Maintenance support is the ability of maintenance organisation to meet production requirements. Otherwise it causes appreciable production losses. For example, inability of the maintenance organisation to respond as soon as a machine fails prolongs waiting time, i.e. increases production time losses. The same thing can be said if the repair takes more time than expected because lack of relevant spare parts or expertise.

If maintenance staff does not possess the right competence, they cannot be expected to perform the right maintenance action at high quality in short time. The right level of competence ensures that the personnel possess the knowledge to use relevant methods and tools required for high quality maintenance work. The personnel also need to be committed to their work, which means that the personnel is committed to follow the established routines, e.g. to lubricate the machine each Monday, but also to perform the maintenance work with high quality and within reasonable time according to given instructions. Otherwise it could mean more frequent failures of more serious nature. Lack of, or ineffective communication in the organisation especially between the operator and the maintenance staff constitutes an additional risk area for failures and disturbances.

C. Production process characteristics

From everyday experience, the machine condition, its technical specifications and maintenance policy are in a strong relationship. In general, production process input characteristics, such as the condition and reliability of producing assets and production procedures influence and are influenced by maintenance performance and quality [3]. For example, old and deteriorated machinery induces many unplanned stoppages and causes production time losses, which in turn demands more maintenance work. Lack of, or ineffective maintenance policy generates causes for faster and severe deterioration, such as the case when no grease is pumped in a bearing and the opposite, when much more grease than required is pumped into the bearing. In both cases a rapid and severe wear and consequently failure would be expected. Further, installation of a rolling element bearing with misalignment leads to severe wear and shorter life length. Also, running the production using special operating conditions and procedures that do not consider the machine technical specifications would lead to faster deterioration, such as the case when repeatedly exceeding the production speed, machine load or pressure, use the machine in a harsh environment, or applying production procedures that do not coincide with machine specifications.

D. Maintenance technical impact

This represents the impact that a maintenance policy can generate on particular attributes at the operative level. These attributes are availability, performance efficiency and quality rate which are expressed in their basic constituents, such as number of the unplanned stoppages, production speed stability, etc. Maintenance policy is defined in BS 3811:1993 as “a description of the interrelationship between the maintenance echelons, the indenture levels and the levels of maintenance to be applied for the maintenance of an item”. In other words, maintenance policy means how the maintenance for each item is planned and performed, e.g. regularly (age-based) or condition-based (vibration-based). In this paper, maintenance policy role is not only to perform repair at need, but rather to detect deviation at an early stage in order to prevent the occurrence of failures and even damage initiation if possible technologically. In general, repair time is strongly influenced by the maintenance policy. The latter decides the technology required for gathering relevant data to perform maintenance actions cost-effectively. A machine that does not get the maintenance work needed will deteriorate at an increasing rate resulting in an increased number of unplanned stoppages.

For example, applying vibration-based maintenance for rotating or reciprocating machines effectively, usually leads to thorough knowledge about damage initiation and development, and detection of potential failure at an early stage [1]. This means that components exposed to deterioration can be detected and replaced before influencing the production process stability, production rate and product quality. Also, increased knowledge about the condition of the machine enables the operator to increase machine production rate to its maximum and stabilize it. A stable production speed is highly rated at the production and sales departments since it make scheduling of production and delivery more secure when the production speed does not vary dramatically. Deviations in all these technical areas mentioned above, i.e. attributes, can be translated at the operative level to production attributes and measure its impact on the production time scale, see Fig. 2. The model quantifies changes in the process to hours of production time. The deviations in the production time can then be summed and the increase/decrease of production time can be assessed.

E. Financial Impact

Translating the total deviations in the production time at the
operative level to a common scale, in this model money, would better clarify the situation and make these changes more understandable in the strategic level as well. Fewer failures stabilizes the production and the need for work-in-process (WIP) storages between production stations will consequently decrease. Additionally, if a company is using for instance condition monitoring technology it is possible to detect damage initiation, damage development and imminent failures, which eases to plan and order spare parts required for performing the maintenance tasks when they are needed instead of keeping a large number of parts in the store. Less spare parts in the inventory means less tied up capital and consequently less costs. Since maintenance role is to avoid unplanned stoppages and disturbances it will secure the delivery of production, which in turn means less or no penalties due to delivery delays. In the strategic level, the figures for the previous and current period are excluded since the focus of the model is on the changes or the difference between the periods. This facilitates the detection of changes without the confusion of the absolute value of each element, which are irrelevant in the model.

When a company has a "faultless" production process, the company will not only benefit through less failures, increased delivery on time and less capital tied up. Also, high quality of personnel competence and environment safety results in less expenses due to less damage in the assets or penalties for pollution. A production with fewer failures, less accidents and fewer expenses in every aspect will also show in the company’s insurance premium [2]. In [3], Al-Najjar presents simple, realistic and transparent formulas that are easy to understand and use for assessing the total maintenance savings that can be done in the production cost, direct maintenance cost, expenses of personnel & environment damage, insurance premium, tied up capital and delivery delay and penalties. This will be further described in the part ‘Financial equations’.

Investments in maintenance policy are usually done in order to enhance the quality and performance of the policy. In other words, they are done to reduce the losses and increase the savings. This is why these investments in this paper are considered as risk capital and we expect payback, i.e. return on investment. If the investment is cost-effective it means its payback is greater than the capital that has been invested, i.e. it is a profitable investment. Otherwise the result will be negative, i.e. more losses.

The profit in this paper is considered as the difference between the investment in maintenance, to make it more accurate and effective, and the savings that have been generated due to this specific investment, which is also a reasonable way of judging the cost-effectiveness of investments in maintenance. This is because the initial maintenance work recommended by the manufacturer represents the minimum required to maintain the machine condition/quality. The additional complications that are usually generated due to modifications and changes in the condition of the machine, operating conditions, production methods and procedures, etc., demands additional maintenance work. Therefore, the investments in maintenance are to meet the additional requirements that were not possible to be fulfilled by the minimum maintenance work.

F. Impact on the strategic level

From everyday experience, it is possible to observe the impact of the operative level on the strategic level (market) [5]. It is also well known that the production performed with less failures and higher quality will increase customer satisfaction.

Satisfied customers lead to a better reputation and more customers, which in turn mean a greater share of the market. Enhanced customer satisfaction and increased market share will eventually result in an increasing stake value. As shown, it is easy to see the logical relationship, but these values cannot easily be estimated quantitatively. There are many factors that may affect customer satisfaction, market share and stake value, therefore a thorough analysis to sort out internal and external factors and quantify their impact is necessary but it lies outside the context of this paper. For example, oil price, natural catastrophes, currency value or wars may all influence market shares in different degrees. Enhancement and control of competitiveness and profitability through controlling the relevant attributes related to the production process is usually ignored by companies.

G. Data sources and data gathering expenses

When analysing the technical and financial impact of all different categories discussed above in the production system, relevant and high quality data are vital. In many cases, data cannot be found in the company’s databases, but are available in the company’s processes and can be gathered. Lack of data makes effective analysis and cost-effective decisions rather impossible. Inaccurate or bad quality data makes the probability of achieving effective identification of the problem areas and root-causes and consequently cost-effective decision a matter of chance.

It is obvious that not all the attributes introduced in different categories of the causes of losses in the model, Fig. 2, can be measured with high accuracy. Some of these attributes may need special studies for identifying how they should be measured and presented, such as the case when considering interactions between maintenance performance and customer satisfaction or market shares. By collecting data and creating databases the company will get a valuable source of information when searching for further improvements. It is thereby an investment and requires resources that must be accounted for.

H. Financial equations

At the strategic level, the model shows the economical result due to the deviations in the production time. [3] provides four simples equations for assessing the financial factors related to maintenance. These equations are briefly described in this article. Formula one to three \( (S_1 \cdot S_2 \cdot S_3) \) implies changes in production time constituting of failures, repair time and short stoppages, respectively. Multiplying the time difference with the hourly production and the profit margin per production unit will give us the total savings or losses in the production cost.
Changes in the Operative level

<table>
<thead>
<tr>
<th>Period</th>
<th>Human Resources and organisation (stoppages because of these factors)</th>
<th>Production process characteristics that can influence and be influenced by maintenance</th>
<th>Maintenance technical impact on these characteristics at the operative level, i.e. Impact of maintenance policy</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Working environment</td>
<td>Maintenance organisation and management tools</td>
<td>Competence, i.e. ability to perform maintenance and operation tasks</td>
<td>Personnel Commitments &amp; communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Previous</td>
<td>0</td>
<td>+1</td>
<td>+1</td>
<td>+2</td>
</tr>
<tr>
<td>Current</td>
<td>-2</td>
<td>-1,5</td>
<td>+1</td>
<td>-1</td>
</tr>
<tr>
<td>Difference</td>
<td>-2</td>
<td>-2,5</td>
<td>0</td>
<td>-3</td>
</tr>
<tr>
<td>Problems area</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Priority 1 (total change -7,5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Priority 2 (total change +3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Priority 3 (total change +7,5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Changes in the Strategic level

<table>
<thead>
<tr>
<th>Period</th>
<th>Financial impact</th>
<th>Impact on market</th>
<th>Data sources</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Production cost</td>
<td>Direct manuetime cost</td>
<td>Expenses of personnel &amp; environment damage</td>
<td>Insurance premium</td>
</tr>
<tr>
<td></td>
<td>+126,900</td>
<td>+50,000</td>
<td>+68,000</td>
<td>+60,000</td>
</tr>
</tbody>
</table>

Impact of deviations in the above on the financial and strategic level

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 The MMME model describes business relationships and mechanisms of transferring the impacts.

Formula four ($S_4$) assess changes of expenses related to maintenance, e.g. direct maintenance cost, expenses of personnel & environment damage, insurance premium, tied up capital, and delivery delay & penalties. The changes are assessed by comparing the cost of the current period with the previous one. Equation $S_1$ to $S_4$:

\[ S_1 = (Y - y) * L_1 * Pr * P_M \]  

\[ S_2 = [(L_1 - L_2) * y] * Pr * P_M \]  

\[ S_3 = [(B - b) * L_2] * Pr * P_M \]  

\[ S_4 = \sum_j (E_{b - E_a})_j \]  

III. APPLICATION EXAMPLE

In this section, we explain the application of the model and its potential in monitoring deviations in production time, maintenance and company’s business by means of an example. In the example, the period taken into account is a quarter of a year which, in general, is a suitable time perspective for many companies. Using a longer period such as a year could mean that deterioration and increasing costs would not be noticed until late, when it instead could be possible to track the deterioration earlier and save money. The model helps to detect deviation at an early stage for avoiding consequences if necessary. In the example, the company considered is a paper mill with continuous production of 24 hours 7 days a week. The data used in this section are partly real data, such as production rate and production losses due to bad quality paper, and partly typical data, such as production time lost due to failures and short stoppages, based on the first author’s practical experience.

In the category of human resources and organisation, the working environment is assumed to become worse due to a higher level of pollution in the air generated due to bad condition of a machine. This has affected the working environment and personnel commitment. The pollution has lead to difficulties in accessing the machines to make inspections, fault seeking and performing the tasks. The production time lost due to more frequent unavailability of operators and technicians because of the working environment is assumed to be 2 hours. Consequently, the situation has led to appreciable decrement in personnel commitment to their tasks, which in turn motivated the personnel to ignore the established routines of daily inspections and maintenance work. The lost production time caused by personnel commitment is assessed to 3 hours. The management tools, such as Computerised Maintenance Management System (CMMS) have not been properly used during this period, and the production time loss due to this is estimated to 2.5 hours. According to measurements, changes in competence level of the personnel is
not affecting the production time during this period.

According to the production process characteristics category, maintenance has led to a better condition of the machine, i.e. less production disturbances except failures and short stoppages, which resulted in 4 hour added production time. The layout in production has been changed and therefore it has become harder to access the machines for maintenance causing prolonged waiting, inspection and repair times. The production time lost due to this equals 1 hour. Changes in the maintenance policy have been made to reduce the downtime of the equipment. The changes have had a great impact on the number of failures, repair time and short stoppages. Production time lost due to failures has decreased by 4 hours compared to the last period, and the repair time has been shortened by 1.5 hours. The number of short stoppages has decreased, prolonging the production time by 3 hours. In accordance with the maintenance policy the operator has decided to lower the speed of the machine due to resonance; the loss equals 2 hours of production time. Better quality assurance technique is used for decreasing the number of rejected items of bad quality. The change is estimated to the equivalence of 1 hour of production time.

From the technical part of the model, we have obtained 3 hours added production. Using a modified version of (1), (2) and (3), where the total added production time multiplied by the hourly production and profit margin, gives us a total saving due to the added time. If the profit margin is 1800 SEK per ton and a production rate is 23.5 tons per hour, this will result in savings of 42,300 SEK per hour, thus a total of 126,900 SEK. In order to calculate the changes in direct maintenance cost, expenses of personnel & environment damage, insurance premium, tied up capital, and delivery delay & penalties, (4) is used. As an example, the direct maintenance cost decreases by 50,000 SEK, expenses of personnel & environment damage by 60,000 SEK, insurance premium by 60,000 SEK, tied up capital by 50,000 SEK and delivery delay & penalties by 30,000 SEK. The cost for the investment to improve the maintenance is -200,000 SEK.

In total, this means savings of 376,900 SEK, which should be compared with an investment of -200,000 SEK in vibration-based maintenance for monitoring the condition of significant components in the machine. The resulting profit of the investment is thus 176,900 SEK and the investment can be regarded cost-effective. The data required had to be gathered by a technician at the company and it required one and a half days of work, which equals 12 hours. The data assessment required 4 hours of additional work. The cost for the technician is 300 SEK per hour, taxes included, and therefore the cost are calculated to 12 * 300 = 3600 SEK and 4 * 300 = 1200 SEK respectively. This means that the cost-effectiveness analysis of the investment cost 4800 SEK.

IV. DISCUSSION AND CONCLUSION

The strengths of the model are that it starts from the technical activities at the operative level and ends with financial figures at the strategic level that is understandable throughout the company, which is required to decide the investments for improvements in the boardroom. It connects the technical and financial impact of every small action being done at a machine or production station of a company to the strategic level where the financial and market related attributes are decided. Furthermore, the model uses transparent formulas that are easy to understand and use with basic education and training. The model is characterised by being concrete, adequate, user-friendly, simple to understand and implement, and developed to be used at a continuous basis. It is also easy to add or remove attributes in the model according to the requirements at the companies. This makes the model very flexible and easy to apply in different business areas. Further, in this model there are no black boxes where no one knows what happens to the input data.

The model MMME can be applied for classifying the causes behind losses, highlighting how relevant working areas interact with maintenance and quantifying their impacts on the company business, see the example above. The model starts from a technical perspective, where the man, machine and maintenance categories’ impact on the production time are elucidated. This effect is then derived to impact on company’s economy and business, which is useful for the maintenance engineer, since money is a language everyone understands, especially decision makers. Showing that an investment pays back during a reasonable time legalize the work with maintenance and authorize continuous work with improvements in maintenance.

This model also shows that improvements in maintenance cost-effectiveness will be visible not only in production cost, but in tied up capital, delivery delay & penalties, insurance premium, and expenses of personnel & environment damage. Understanding the complex interactions within a company helps the company to develop and gain competitive advantages.

REFERENCES