QUANTIFYING THE EFFECTS OF PRODUCTION MAINTENANCE DECISIONS USING DISCRETE EVENT SIMULATION

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Abstract: Use of simulation to analyze and plan maintenance activities is still limited compared to planning production activities. The paper discusses a simulation based approach to quantify the effects of maintenance decision making by identifying the related performance indicators. The aim of the paper is to quantify the production maintenance related decisions, in terms of Key Performance Indicators (KPIs) determined trough interwievs and simulation. The approach is exemplified in a manufacturing case-study. The results show that use of simulation tool has the potential to be a strategic decision support tool for production maintenance in the production system.

Keywords: Maintenance Planning, Decision Support System, Discrete Event Simulation, Key Performance Indicators

1. INTRODUCTION

As the amount of input data to consider increases, decisions made in industry have become more complicated. To motivate changes, managers need a state-of-the-art tool to support decisions related to planning, operations, and design (Rohrer 2002). The term e-maintenance was developed to merge two trends in industry; the growing importance of maintenance to ensure proper running of machines, efficiently and safe, and the rapid development of Information and Communication Technology (ICT) tools (Holmberg et al., 2010). The e-maintenance concept is a computerized maintenance management system, which uses various tools to monitor degradation. E-maintenance is used as a decision support tool to optimize asset utilization and enables quick and right maintenance decisions to be made. To describe the development of Maintenance Decision Support system (MDSS) there is need to study maintenance procedures in production systems. Huang et al. (2003) consider methods like modeling and simulation as the most reliable method in studying dynamic performance of production system.

There are several strategic approaches to maintenance planning. Historically, corrective maintenance, or run-tofailure and periodic maintenance were commonly used. Today, the current strategic approaches moves in direction of increasing opportunity maintenance, time-based maintenance, and condition-based maintenance. In the future, to avoid unpredictable failures or having to stop production in unnecessary cases, the optimal solution is to know continuously the condition of the machine and take service action and repair on a priority based technique (Gopalakrishnan et al. 2013). The priorities and condition monitoring also depends on the interaction between different machines in the system. Therefore, there is need for thinking about maintenance from a system level perspective and not just from machine level. Simulation on a system level enables reliable methods to assess the dynamic performance of the production system (Huang et al. 2003). Stochastic simulation can thus be used to evaluate system performance in the face of uncertainty and predict failures based on the previous behavior of the system (Hederson and Nelson 2006). This paper aims at identifying Key Performance Indicators (KPIs) related to preventive and corrective maintenance and evaluate the different maintenance decisions by these KPIs using DES (Discrete Event Simulation). Using DES the cost of maintenance, machine's technical availability, system throughput, and the relation between preventive and corrective maintenance are evaluated. Semi-structured interviews are made with the industry employees to map the current practices and analyze the future needs.

2. FRAME OF REFERENCES

2.1 Preventive and corrective maintenance in production system

Maintenance is currently critical for organizations to maintain competitiveness (Holmberg et al., 2010). The purpose of having a maintenance plan is to minimize the combined cost of running the business and maintaining the production. A manager has a range of maintenance strategies available to reach that aim, mainly corrective maintenance (CM), time-based maintenance, design out, and condition-based maintenance. This paper focuses on corrective maintenance (CM) and preventive maintenance (PM); performed to reduce probability and consequence of equipment failure.



Fig. 1. The Bathtub curve.

CM is referred as "maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function", while PM is referred as "maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or degradation of the function of an item" (SS EN 13306, 2001). However, finding the optimum ratio between CM/PM is difficult, especially finding the optimal use before exchanging parts. According to the Bathtub curve, new equipment tends to have a high probability to fail during the first weeks of operation due to installation problems, see Figure 1 (Mobley, 2004). After this period, the probability of failure is relatively low but constant, until a point in time when probability increases again, due to equipment worn out.

2.2 Simulation and Maintenance

DES is used to model and analyze various fields, mainly due to its stochastic modeling abilities. It allows for accumulation of several trials, thereby achieving statistically significant results at the end. Simulation is typically used to determine critical factors in a system. Modeling a system enables tests and analysis of changes of a system over a compressed period of time. There are several examples of studies where simulation was used to analyze and improve maintenance activities. Kaiser (2007) focused on comparing the effect of different maintenance strategies on a common manufacturing model. The model used mathematical degradation equations to model a components lifetime in a system. Suliman and Jawad (2012) presented a mathematical model to optimize PM age, time, and lot size for a single unit production system. Here, PM age was defined as the time between PM activities. Gopalakrishnan et al. (2013) investigated how maintenance strategies can be used in production planning and the effect on production performance and robustness of production plans. In addition, the simulation was used to demonstrate how changes in operators' responsibility increased productivity. Ali et al. (2008) used DES to identify critical stations through optimization. The simulation model was also used to identify an optimal system design, and to schedule maintenance activities. Altuger and Chassapis (2009) used DES to analyse how new equipment installation affected the system performance.

2.3 KPIs of Maintenance

KPIs are quantifiable and strategic measurements which are set in relation to management goals to reflect an organization's performance. KPIs are therefore unique for each organization. According to Wireman (2005),

KPIs are developed at a corporate level and thereafter at subsequent levels or departments to avoid conflicting indicators. International Standard (2011) recommends a selection of KPIs, considered more significant in relation to maintenance. Among these are mean operating time between failure (MTBF), mean time to failure (MTTF), mean time to repair (MTTR), and ratio of time spent on CM to total time spent on maintenance (CM ratio). The ratio provides an indication of a system's reliability, where the lower CM ratio, the better system reliability. Smith and Hawkings (2004) suggests a list of common KPIs used to monitor maintenance activities,

- MTBF by total operation and by area, and then by equpiment
- MTTR maintainability by individual equipment
- Overall Equipment Efficiency (OEE)
- PM labor hours divided by emergency (CM) hours
- Number of workorders as a result of PM inspections divided by number of CM

3. METHODOLOGY

This chapter describes the methodology used to fulfil the aim of this study. The aim of the paper described in the introduction chapter is exemplified using a healthcare industrial case-study in a batch production process. The main approach was to identify and confirm relevant KPIs using litterature and interviews. These KPIs was used in a DES model to quantify the effects of preventive maintenance, thus to identify how preventive maintenance may affect the need of corrective maintenance. Data from three different time periods with various maintenance was collected and studied. In order to compare the time periods, each period was simulated using DES to equate planned production time and external faults between the time periods. Based on information received during interviews, one of the periods was considered to be a more accurate representation of normal production. This period was therefore used as a base model in the analysis. The simulation study has followed the steps for simulation projects described by Banks et al., (2010). The study started with semi-structured and unstructured interviews. (DiCicco-Bloom and Crabtree 2006) mainly to map the current practices and needs regarding maintenance. The interviewees included a maintenance manager, a maintenance engineer, operators, and technicians. An interview was also performed with a financial operations controller to gather financial data and make realistic assumptions. To assess the usability and identify causes of usability problems, a cognitive walkthrough (Polson et al., 1992) of the user-interface was performed with the maintenance manager and maintenance engineer on the designed DES user-interface. It was used to evaluate current KPIs and identify additional KPIs. Furthermore, the walkthrough was used to evaluate whether the simulation model and its user interface could be an appropriate decision tool for maintenance planning.

3.1 Use-Case Description

The simulated model tries to replicate the real production system consisting of three sub lines, further divided into 47 sections. The sub lines handle three types of parts, put together at two merging points. The products are mainly handled in batches of six. The sections are synchronized without supporting buffers in-between the sections. The production system is designed so that if one section stops the entire line stops. The line is supposed to run continuously except for an 8 hours stop each week, which is scheduled for PM. In addition, the line is shut off if the production target is achieved. Three operators are responsible for production line, including setup, material filling, quality control and repair of less complicated failures. Six operators are responsible for packing the final product at the end of the line.

3.2 Experimental plan

The work procedure for the paper followed the following steps.

- Step 1: Semi-structured and unstructured interviews to map the current and future KPIs.
- Step 2: Cognitive walkthrough on the DES user-interface to evaluate the DES.
- Step 3: Simulation of the production system to compare and evaluate the KPIs.

Unlike traditional simulation experiment, there is no future state model. The simulation model is developed for the current state using historical data. Three cases were developed with data obtained from quarter 3 (Q3) in 2013, quarter 4 (Q4) in 2013, and quarter 1 (Q1) in 2014. Quarter 4 (Q4) in 2013 was selected as the base model. Each simulation was run for 91 days (one quarter), a warm-up period of 168 hours. The runs used 5 replications, meaning that the experiments for each condition were run 5 times.

4. SIMULATION MODEL

4.1 Model Building

The building of the simulation model was based on observations of the production line, guided tours by the operators, interviews, and of process descriptions. Automod® was used to build the model and run the simulations. The base model represents normal production in terms of planned production time and factors affecting the planned production time, for example availability of raw material, quality, etc. Based on interviews, conditions in Q4 2013 were chosen for the base model. To compare the KPI's of the different quarters, the same conditions were used in the simulation of two additional quarters, Q3 2013 and Q1 2014. A user-interface was furthermore connected to this model to enable the model to later be updated.

4.2 Abstraction Level

The authors have been making assumptions and simplifications in order to fill out data where data was missing and to handle the complexity of reality. The main assumptions and delimitation are:

- The simulation model will only take a selection of spare parts, based on an ABC analysis of the annual cost of used spare parts.
- The difference between stop time and time spent on CM by technicians is assumed to be time spent on repairs by operators.
- Both fixed and variable costs of a product will be modeled as variable costs in the simulation model, since cost is allocated per product.

4.3 Verification and Validation

Verifying the simulation model is primary to ensure an error free code (Sargent, 2010). Computerized model verification was used to ensure that the conceptual model and the simulation model are consistent. Another primary technique was to go through the code step by step to see if it is programmed in a correct way. The model was validated to ensure the model corresponded to the real system. The following techniques have been used (Sargent, 2010):

- Animation: Observing the operational behavior and movements of parts graphically.
- Event Validity: Using the comparison of the occurrences of events in the model compared to the occurrence of events in the real system.
- Historical Data Validation: Using historical data to compare if the model behaves as the real system.

5. RESULTS AND ANALYSIS

5.1 Results from Interviews

Maintenance decisions at the company today. The important result from the interviews was the decision to increase PM in quarter Q4. Quarter Q3 had limited PM tasks allocated to stations on the production line. There was a realization on importance of PM tasks from the management. The preventive maintenance task is performed according to pre-scheduled maintenance points. The interval between specific points varies in between weekly performed maintenance and maintenance performed once a year. There is also the decision of stopping the entire production on 1 day (Thursday) in a week for PM of the entire production line. The scheduled PM is based on a set time interval, and does not consider the number of produced products as well as the current state of production. In addition, service requests for the stations were added when discovered, either during a scheduled PM or during production. Service requests are identified problems by operators or maintenance personnel during their work and scheduled during unplanned production. All production stops are registered by a separate industrial system. Stops shorter than 1 minute are automatically registered as short stops while longer stops require an operator to manually specify which section failed. This ensures all stop times were included. CM is done by either the operator or maintenance technician depending on the severity of the stop. The company are currently working on prioritizing PM tasks and have started to analyse the factory on a line level in addition to the factory level. The company have no previous experience with simulation.

KPIs at the company today. KPIs relating to maintenance have recently been implemented. During the quarter Q4, 2013, the department started following up on technical availability, ratio of scheduled PM/CM by technician/service request, scrap due to machine failure, MTBF and MTTR. The production support department has focused on measuring technical availability since it shows the department's impact on productivity. Both the maintenance manager and the maintenance engineer gave current KPIs a score of four on the adequate scale

from one to ten. The motivation behind the low score was that KPIs are only evaluated on the entire production line and not yet on a station level.

Cognitive walkthrough. Results from the cognitive walkthrough showed positive attitude towards simulation as a decision tool for maintenance planning. Furthermore, determined KPIs to use in the simulation model, described in section 5.2, were considered as relevant for maintenance planning.

5.2 Key Performance Indicators

KPIs used to quantify effects of maintenance were determined based on interview, cognitive walk-throughs, and theory. From interviews, the authors identified relevant KPIs used at the company today; MTBF, MTTR, and technical availability. These were currently measured on a factory level. In order to evaluate in detail the maintenance related decisions for the production line in focus, the authors used simulation to analyze these KPIs on a station level as well as system level. In addition, the results from the cognitive walkthrough of the user-interface showed an interest in measuring the cost of various maintenance activities (e.g. PM and CM) in relation to total maintenance cost for the different maintenance decisions made. Another cost related KPI was determined; return on assets (ROA), which give an indication of how profitable a productions line is in relation to its assets. From literature, CM ratio was used.

5.3 Discrete Event Simulation

System Performance. The performance was measured using technical availability, MTBF and MTTR. Furthermore, the total fault time was divided into failures which can be fixed by an operator and failures which requires a maintenance technician. With respect to the decision of increasing PM, Figure 2 shows an increase in MTBF and technichal availability between Q3 and Q4, meaning failures occurred less frequent. From Q4 to Q1, both technical availability and MTBF decreased. In regards to MTTR, it decreased through all quarters, meaning that mean downtime for a stop has continuously become shorter, this is due to service requests and decreased failures. The figure also show that the standard deviation on all KPIs have reduced, indicating increased stability, which is essential in order to understand and perform correct maintenance procedures. The values can be obtained in Table 1. Further, comparison between the repair time for operators and for technicians show that technicians were working a major part of total fault time in Q4, while operators tend to fix more stops in Q3 and Q1, see Figure 3.



Fig. 2. Change in technical availability, MTBF, and MTTR.

	Q3 2013	Q4 2013	Q1 2014
Technical Availability	62%	85%	82%
Standard deviation	5%	4%	3%
MTBF (hrs)	0.296	0.436	0.344
Standard deviation (hrs)	0.029	0.03	0.023
MTTR (hrs)	0.204	0.086	0.08
Standard deviation (hrs)	0.015	0.014	0.012

Table 1. Values described by Figure 1.



Fig. 3. Distribution of repair work carried out by operators versus technicians.



Fig. 4. Increased time for PM decreased the total fault time for a specific station. Fig. 5. Increased time for PM increased the total fault time for a specific station.

The PM was increased between quarter Q4 and quarter Q1. The increased PM was expected to reduce the total fault time of the production line. But a holistic analysis of the entire production line shows an increase of total fault time between Q4 in 2013 and Q1 in 2014. Since the production line consist of 47 stations, each station was analyzed to evaluate the relation between PM and CM. The stations with similar behavior were grouped. There were four significant groups and they followed increased PM resulting in reduced total fault time, increased PM resulting in increased total fault time, increased PM resulting in total fault time kept at zero, and decreased PM resulting in increased PM.

Comparing total fault time and total PM time resulted in the same significant groups. Simulation results identified 10 stations which has increased total PM resulted in reduced CM and 12 stations where decreased total PM increased CM. Both these behaviours indicates a relation between PM and CM. Though, other 12 sections indicated the opposite behaviour; increased PM resulting in increased total fault time. These stations have to be further analysed to determine if the additional PM tasks have introduced new effects or if the failures are a consequence of a components likelihood of failure according to the bathtub curve. 7 stations were included in the last significant behaviour group; increased PM resulting in total fault time kept at zero, all showing signs of having PM work done when there is little or no risk of failure. Also in these stations the PM has to be further analysed. Figure 4 and Figure 5 show examples of sections demonstrating the opposite behaviour. In Figure 4, the total fault time reduced as PM increased while in Figure 5, total fault time increased as PM increased.

Cost. The cost of different maintenance activities (PM and CM) was compared between the three quarters to analyze the maintenance decision changes during those quarters. The cost was calculated based on time and hourly cost of packaging personnel, operators and technicians respectively, and any spare parts. Figure 6 shows how total cost of maintenance has varied between the quarters. The largest difference is 63 relative percentages reduced total cost in Q4 compared to Q3. In Q1, total cost increased slightly by 4% compared to Q4. Figure 7 shows the distribution between PM and CM. The CM cost ratio of total maintenance costs is 89%, 69%, and 77% for the quarters, respectively. The standard deviation for the cost of CM is 12%, 7%, and 7% (relative Q4) respectively for the quarters, indicating a higher stability. Further, Figure 7 show that cost of PM in relation to total maintenance cost has increased from 11% to 31% in Q4 compared to Q3, while it reduced to 23% in Q1. These cost analysis results are directly reflected from the increased PM efforts during Q4.



Fig. 8. Cost of spare part and cost of personnel compared to total CM.

Fig. 9. Cost of spare part and cost of personnel compared to total PM.

As mentioned above, the cost of maintenance activities was divided into cost of personnel and cost of spare parts exchanges. In order to determine the major cost of maintenance, these were analyzed and compared between the quarters. Figure 8 indicates it is evident that the major cost factor of CM is personnel costs with 98%, 85%, and 81% of the total maintenance cost respectively. This means that the major cost of a breakdown is personnel waiting instead of doing value added work. Regarding the cost of PM, cost of personnel was only 56% in Q4 compared to 96% and 84% respectively for Q3 and Q1, see Figure 9. Even if the relative cost of spare parts exchanged in PM was higher in Q4, total maintenance cost and total fault time was lower compared to the orther two quarters. Figure 3 shows that the major part of total maintenance cost is the cost of CM, which means that a lower total fault time reduces the total maintenance cost. Furthermore, the results show that Q1 had a higher total fault time compared to Q4, but a lower rate of assistance from technicians and a lower MTTR, described by Figure 3 and Figure 2 respectively. This suggests that Q1 had more frequent, but shorter stops handled by the operators. The increase in stoppages and decrease in average stop time, indicates that the increase in number of spare part exchanges in Q4 resulted in an increased number of small stoppages in Q1. According to the bathtub theory, these stoppages should be due to installation problems.

Return on assets. The economical KPI; ROA, was calculated using products produced and cost of CM between the quarters. The cost and sales prices for one product, and the companys total assets was assumed to be the same in order to compare the quarters. From Q3 to Q4, ROA increased by 31% and from Q4 to Q1 it decreased by 5% which corresponds with the increased technical availability from Figure 2. Since ROA changes depending on products produced and cost of CM, the curve of ROA follows technical availability in Figure 2.

6. DISCUSSION

This study shows the use of simulation to analyse maintenance decisions in a similar way as production decisions in current scenario. DES was used to equate external factors to compare three quarters where time spent on PM could be compared to fault time. Simulation has the ability to analyse a system on different detail levels. It is therefore important to understand the performance indicators that respond to a company's corporate goals, site goals, and department and individual goals. These KPIs helps in evaluating the production system critically and enables in decision making. The simulation model was constructed so that the user is able to test

possible improvements before implementation. Furthermore, it is designed so that the user is able to change input variables and update the system based on the current production data. Therefore, the user is able to put in updated input variables and compare these with previous results in order to discover a relation between PM and CM or to identify a trend in how each station reacts to planned maintenance procedures.

Furthermore, it is important to state that a model required correct input in order to generate a realistic output. Since operators and technicians are responsible for coding failures and performing maintenance procedures, it is important for management to communicate and involve the affected personnel in on-going change initiatives in order to sustain improvements.

The interesting step for future work could be on analysing on both station and system level maintenance strategies. Gopalakrishnan (2013) discussed the priority-based planning of maintenance activities on a system level using DES. Similarly other strategies for planning maintenance using different criticality analysis methods like bottleneck analysis are possible. The different KPIs along with strategic planning will help in finding robust plan for production system for improved sustainability and productivity. On station level the reduction of MTTR for operators using ICT tools and its effect on the system could be analysed. With these uses of DES, it is safe to say it has the potential to be a power full, strategic decision support tool for maintenance planning.

7. CONCLUSION

This paper presents an approach to demonstrate and analyze the effect of maintenance decisions by using DES as a decision tool. The simulation model identified critical sections and shows the economic effects of possible maintenance improvements. Since the model is connected to an interface, the user is able to update various input parameters in order to receive an updated version of current KPIs values. KPIs received from the model; MTTR, MTBF, CM ratio, technical availability, and ROA are determined based interviews, cognitive walkthroughs, and on KPIs used at a factory level. Apart from being used as a decision tool, the model shows the importance of documentation, communication, and involvement in order to achieve maintenance targets. Overall, a greater understanding of the company's resources and the relation between cause and effect will have a sustainable impact throughout the factory.

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