7th International DAAAM Baltic Conference
"INDUSTRIAL ENGINEERING
22-24 April 2010, Tallinn, Estonia

DEVELOPMENT THE MAINTENANCE PLAN: MAINTENANCE ACTIVITIES ON OPERATIONAL LEVEL

Bjorklund, S.; Pribytkova, M. & Karaulova, T.

Abstract: *This article focuses on the operational level of production enterprise activities and considers the suitability of failure mode and effects analysis (FMEA) which is a central element of Reliability Centred Maintenance (RCM), and periodic maintenance problem (PMP) solving for the case production line. FMEA provides the data for PMP in the context of failures and bottlenecks in machines and equipment. PMP uses operational research methods to find optimal maintenance plan. This combination of two methods (RCM/FMEA and PMP) becomes a powerful tool for reducing total cost of maintenance and diminishing the frequency of production line failures. The case production line is tested using the combination of FMEA and PMP.*
Keywords: maintenance strategy, FMEA, RCM, maintenance optimisation, PMP, mathematical modelling.

1. INTRODUCTION

Nowadays production enterprises of single industry compete by emphasizing on every aspect of business activities. The high level of automation supports the efforts of a company to be on a higher position comparing to others. This so called state-of-art automation requires professional approach in issues of machines maintenance. Ben-Daya and Duffuaa [1] find that the activities connected to equipment maintenance are becoming more evident and important in context of quality and manufacturing costs. That means that companies indicate increasing of the maintenance expenditures and maintenance personnel. Garg and Deshmukh [2] discuss that in some industries it is not uncommon that the maintenance and operations departments are the largest, and each comprises 30 percent of the total manpower.

Unfortunately though the methodologies elaborated for creation of maintenance management systems are mostly a key for optimization of maintenance strategy, these usually do not offer an action plan for an operational level and this is often the problem for engineers. That is, a lot of methods consider planning of maintenance activities on production enterprise simply emphasize too much on strategy which is usually connected to top and middle-level management responsibilities. That means staff on operational level often fulfils maintenance tasks which are too general and hardly transferable to maintenance plan. According to Jonsson [3], it is not enough to formulate strategies, because management commitment to the maintenance goals has also to be present to make the integrated system work.

However the main disadvantage of maintenance techniques for operational level is that these require input information which is difficult to obtain. This view is supported by Sharma et al., [4] and they point out that many of these (input) factors are not easy to evaluate because of uncertainties associated with estimation of the failure/repair characteristics of the components/units of production system.

Taken together these considerations suggest that:

• The majority of maintenance techniques are designed for top-management level and therefore have difficulties with implementation into production system.
• Those maintenance techniques for operational level require input information for producing maintenance plan.
This article is solving these two problems and considers implementing the combinations of two techniques on the case production line. FMEA as the first step is used for revealing gaps and bottlenecks through the analysis of failure effect in the case production line and after assessment these results are transferred to PMP. As the second step, PMP, which is fully based on mathematical modelling, solves planning problems by the means on operations research - results of PMP represent a maintenance plan to follow. The maintenance plan for a case production line as the main outcome of the practical implementation of two-staged method combination is analyzed and the assessment of possible benefits of maintenance plan is made. The suitability of the combination of two methods – RCM/FMEA and PMP for other or similar production systems is considered.

2. MAINTENANCE TECHNIQUES

Maintenance is required for all types of machinery. The type of maintenance that is performed can be defined as either preventive or corrective maintenance. Preventive maintenance is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of a failure. Corrective maintenance is carried out after a failure and is intended to repair the system. In other words, preventive maintenance is performed before a failure and the corrective maintenance is performed after the failure occurs.
Figure 1 shows an example of condition based maintenance along with corrective and scheduled maintenance in context of time and condition of equipment.

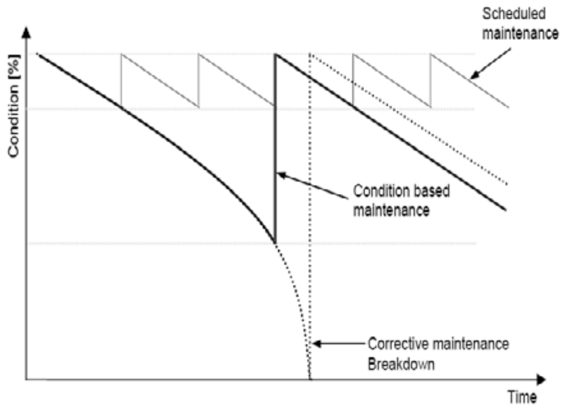

Fig. 1. Condition based maintenance compared to scheduled and corrective maintenance

Garg and Deshmukh [2] propose to split all maintenance activities performed on production enterprises into six main groups:
- maintenance optimization models
- maintenance techniques
- maintenance scheduling
- maintenance performance measurement
- maintenance information systems
- maintenance policies

The first three activities can be connected to operational level of the production enterprise. Authors of this article propose to choose PMP technique for the case company as this scheduling technique allows planning maintenance on operational level and in the same time is easy to customise.

3. PERIODIC MAINTENANCE PROBLEM

In context of planning the maintenance activities or in other words of scheduling the periodic sequence of maintenance, the method proposed by Grigoriev et al., [5] is the most robust one. The reason is that the PMP model considers various machines and maintenance of them during the several periods. Although the model considers machines separately, these could be combined together in the production line. As the mathematical models used for planning activities on the enterprises mostly generalize the problem, these should be adapted for needs of this very product line.

The model of Grigoriev et al., [5] can be formulated as follow. The production system uses various machines, which have index $i = 1 \dots m$ and maintenance the machines takes place in different periods $t = 1 \dots n$. During the period *t* no more than one machine can be serviced. When machine i is serviced, the constant servicing cost of b_i is added to the total cost of operating the machine, regardless of the period. At time moment *t*, a machine *i* that is not serviced during the current period and is in operation, incurs an operation cost of a_i. It is assumed that the operating costs of a machine increase linearly with the number of periods elapsed since last servicing that machine. The problem is now to determine a maintenance schedule, i.e., to decide for each period which machine to service (if any), such that total servicing costs and operating costs are minimized.

The PMP can be also reformulated in equations.

The maintenance variable k_{it} is binary, which means it equals 1 if the maintenance takes place and 0 if does not. Let Y_i be the number of periods in the planning horizon in which maintenance took place and N_i the number of periods without maintenance and obviously.

$$N_i = m - Y_i. \quad (1)$$

The total cost, TC of utilization the machines in production line consists of two components

$$TC = TC_{maintenance} + TC_{utilisation}. \quad (2)$$

Therefore the objective is to minimise the sum of two components

$$\min TC = \sum_{i=1}^{m} b_i \cdot Y_i + \sum_{i=1}^{m} a_i \cdot N_i \quad (3)$$

in the frame of constraints

$$\sum_{i=1}^{m} k_{i1} = 1, \sum_{i=1}^{m} k_{i2} = 1, \dots, \sum_{i=1}^{m} k_{it} = 1 \quad (4)$$

$k_{it} = binary$, which means only one machine can be serviced during single period.

The advantage of PMP in the frame of the article is that it considers maintenance activities on the machine level.

The main disadvantage of the methods is that it requires input information which is hard to obtain. That means some other procedures must be performed on the production line.

4. RCM /FMEA

The approach of Reliability Centred Maintenance (RCM) could provide the data required as an input for PMP model. RCM is method for creating effective maintenance strategies. The term reliability-centred maintenance refers to scheduled-maintenance program designed to realise the inherent reliability capabilities of equipment. One of underlying assumptions of maintenance theory was always the presence of a fundamental cause-and-effect relationship between scheduled maintenance and operating reliability.

According to Sharma [6] the Failure Modes and Effects Analysis (FMEA) methodology has been used for many years in many different industries to help analysts to understand the potential failure modes in design, then to evaluate the risk posed by those failures and identify the most appropriate corrective actions. The same analysis technique is a central component of RCM methodology, which has also proven to be effective for developing safe, reliable and cost-effective maintenance policies for equipment.

The RCM analysis process in Figure 2 includes performing a Failure Mode, Effects, and Analysis (FMEA), selecting significant functions, and performing task evaluations and task selections [7].

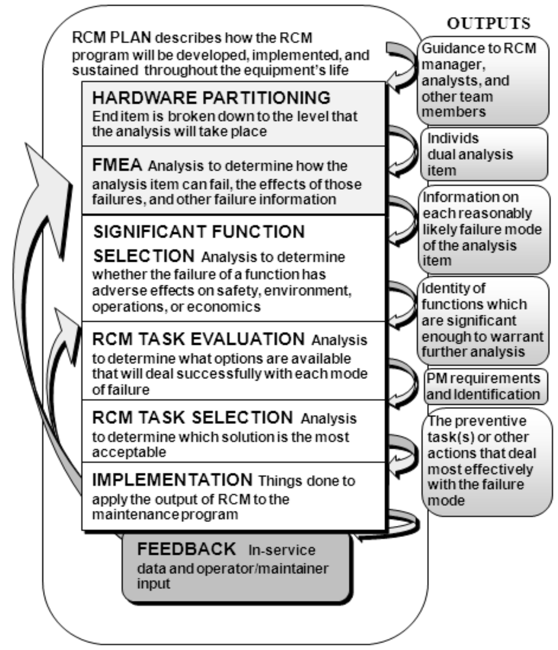

Fig. 2. RCM process [7]

The FMEA analysis has as an outcome the equipment in the production line, the most typical failures of the single machines and the possible effect. This data can be transferred into the PMP for the planning the maintenance activities.

5. THE CASE PRODUCTION LINE

Present study considers the process of retractors' production line. A retractor is the main part of the car seatbelt mechanism. The layout of the line is illustrated in the Figure 3. The line is divided into 13 working stations responsible for certain type of process operation. All the stations are jointed into a conveyor.

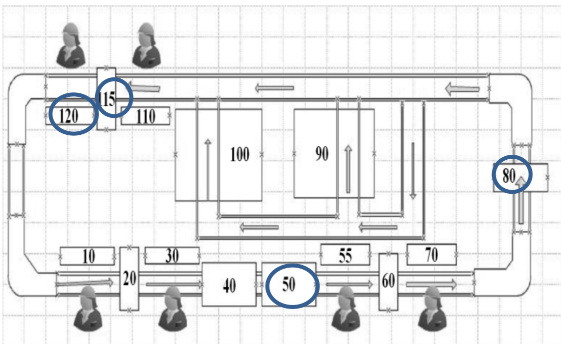

Fig. 3. Layout of the retractors' production line

In the frame of the article the case production line is analysed.

No. of working module	Description of working module	Failure mode	Cause of failure	Part to be fixed	Frequency of failures per month
50:1	Assembling of fixing pin into frame	Pin is stuck into feeding equipment	Dirt, obstruction	Feeding channel	4
50:2	Assembling of fixing pin into frame	Misalignment between tool and frame	Tool wear	Assembling tool	0.16
50:3	Pins supplying system	Accumulation of pins	Dirt in supplying system	Supplying channel	4
80	Removing of latching mechanism of tooth gear	Latching mechanism not removed	Wear of gripper	Gripper	0.25
120	Screw driving	Not enough depth of screwing	Wear of screwdriver head	Screwdriver head	0.25
115	Retractors lifting system	Retractor is not lifted	Looseness of bolt joint	Bolt joint	0.16

Table. 1. The outcome of FMEA

The FMEA analysis showed the six bottlenecks of production line (see Table 1) – three modules in machine 50 and machines 80, 120 and 115. The causes of failures which are connected to wear of parts are considered. The working modules of interest are also marked by circles in Figure 3.

The main outcome of FMEA analysis is that it provides the necessary data for periodic maintenance problem solving. Working modules which are bottlenecks in production line, the failure mode, the cause of failure and part to be fixed and frequency of failures – this information can be transferred into PMP model.

The process of transferring the output information of FMEA into the inputs of PMP is based on the exact type of machines being utilized on the enterprise and therefore are not shown in the article. This transferring consists of calculation of a_i and b_i coefficients which are essential for solving PMP.

The solution is found and shown below using the classical approach of operations research. For convenience is it proposed to solve the periodic maintenance problem directly in *Excel Solver*.

In cells B2 across to G2 (Fig. 4) the b_i coefficients are presented which denote the cost of machine maintenance.

	A	B	C	D	E	F	G	H	I
1	cost of	b1	b2	b3	b4	b5	b6		
2	maintenance, bi ->	5	12	7	32	14	25		
3									
4	growth rate of	a1	a2	a3	a4	a5	a6		
5	machine usage, ai ->	10	7	3	4	12	12		
6									
7	No. of machine->	No.1	No.2	No.3	No.4	No.5	No.6		
8	Period1	0	1	0	0	0	0	1	
9	Period2	0	0	1	0	0	0	1	
10	Period3	1	0	0	0	0	0	1	
11	Period4	0	0	0	0	1	0	1	
12	Period5	0	1	0	0	0	0	1	
13	Period6	0	0	1	0	0	0	1	
14	Period7	1	0	0	0	0	0	1	
15	Period8	0	0	1	0	0	0	1	
16									
17	periods of servicing, Yi ->	2	2	3	0	1	0	∑	
18	cost of maintenance, bi*Yi - >	10	24	21	0	14	0	69	$\sum_{i=1}^{m} b_i \cdot Y_i$
19	periods of not servicing, Ni ->	6	6	5	8	7	8	∑	
20	cost of utilisation, ai*Ni - >	60	42	15	32	84	96	329	$\sum_{i=1}^{m} a_i \cdot N_i$
21									
22	total cost							398	

$$\min TC = \sum_{i=1}^{m} b_i \cdot Y_i + \sum_{i=1}^{m} a_i \cdot N_i$$

Fig. 4. Spreadsheet of periodic maintenance problem at the case production line

In cells B5 across to G5 the a_i coefficients are presented which denote the cost of machine utilization per single period if machine is not serviced.

Decision variables represent a maintenance plan or 6x8 ($m = 6, t = 8$) matrix in which each cell is binary or in other words can be equal to 1 if the machine is service in the period; otherwise the cell value is 0.

Periods of servicing Y_i are represented by cells B17 across to G17 and for instance, B17=COUNTIF(B8:B15,1).

Periods of not servicing N_i are represented by cells B19 across to G19 and for instance, B17=COUNTIF(B8:B15,0).

The balancing constraints are represented by the cells H8 down to H15 and where, for example, H8=SUM(B8:G8).

That means H8 reflects the number of machines serviced in a single period and therefore cells H8 down to H15 should be equal to 1.

Total cost of maintenance (3) is in cell H22, which has to be minimised and where H22=H18+H20.

Solver is configured so that the objective is to minimize H22 cell (the total cost) subject to constraints (Fig. 5). These constraints are as follows. All decision variables are integer and are in range from 0 to 1. That means the only possible value of decision variable is either 0 or 1 and doing so the decision variables become binary *indirectly*. The reason is that for *Excel Solver* it is more suitable because searching the optimal solution with *purely* binary decision variables demands more resources.

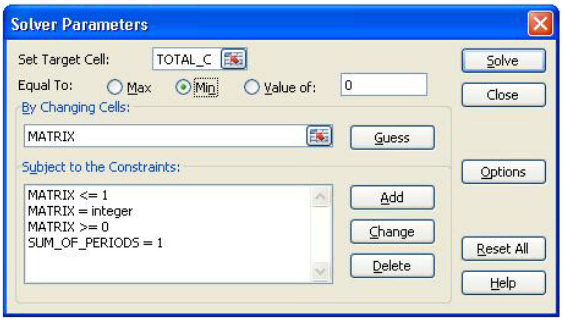

Fig. 5. Solver Parameters for the PMP

The results on the table represent a periodic maintenance plan (Fig. 4). The combination of maintenance activities in the frame of given conditions reflects the optimal maintenance schedule. The solution satisfies all constraints, that is number of machines maintained during a periods is equal to one. Accumulated cost, which includes cost of maintenance and the increasing of expenditures of machines utilization, is optimal.

6. DISCUSSION

The solution found by the means of *Excel Solver* can be considered as optimal. However it should be noticed that this approach of combining the two methods – FMEA and PMP has revealed several limitations. First is the realization of *Excel Solver* mathematical apparatus. The maximum of decision variables is equal to 200 and that means the largest model has 10 machines and 20 maintenance planning periods. However there is more tight limitation – *Excel Solver* tries approximately 20000 combinations of decision variables in 1.6 hours for 6x8

model. After this time simulation stops and therefore does not reach the solution searching preset time. The reason is that *Solver* needs much more resources for integer and binary problems. This point of view is supported by *Solver* developers.
Integer variables make an optimization problem non-convex, and therefore far more difficult to solve. Memory and solution time may raise exponentially as more integer or binary variables are added [8]. The possible solution in this case is to transfer model into *Matlab* or to develop own software application.

7. CONCLUSION

The combination of two methods is suitable for the case production line. FMEA and PMP combination can be easily integrated in the production system. FMEA could be applied to the manufacturing systems of any complexity from one component of equipment to single machine and production line. PMP can be used for planning maintenance activities for various numbers of machines and different planning horizons. This means the combination of FMEA and PMP can change its scale.
On the other hand the practical realisation of PMP need to be reviewed in future studies and experiments. The development of software application may become necessary for further researches.
The test procedures on the enterprise show that the combination of methods is suitable exactly for operational level of production company.

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DATA ABOUT AUTHORS

M.Sc. Sergey Bjorklund
Festo OY AB Eesti Filiaal, Laki 11B, 12915, Tallinn
sergey.bjorklund@festo.com
M.Sc. Marina Pribytkova
AS Norma, Laki 14, Tallinn
marina.pribotkova@autoliv.com
Ph.D. Tatyana Karaulova
TUT, Department of Machinery, Ehitajate tee 5, Tallinn
tatjana.karaulova@ttu.ee