Concept of the FMEA method-based model supporting proactive and preventive maintenance activities

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Abstract. Proper planning of preventive maintenance (PM) is crucial in many industries such as oil transmission pipelines, automotive and food industries. A critical decision in the PM plans is to determine frequencies and types of maintenance actions in order to achieve a certain level of system availability with a minimum total cost. For any given interval, a decision must be made to perform one of the three actions on each component; inspection, preventive repair and preventive replacement. Any of these activities has different effects on the reliability of the components and the corresponding distinct costs based on the required recourses. The intention of the authors is to develop a concept of supporting the process of planning and scheduling of preventive and proactive activities using the FMEA method for failure analysis. According to the concept of sustainable production, the failure will be assessed from different perspectives, not only in terms of product ion, but also considering operators and process safety as well as threats to the environment. The concept developed and presented in the paper in combination with IT support is the basis for risk assessment and establishment of cause and effect relationships to prevent failures and / or minimize their consequences.

1. Introduction
Production facilities continuously strive for reduction and elimination of unpredictable (additional) costs related to unscheduled downtime of technical equipment. New management concepts such as Lean Manufacturing, Green Manufacturing and Sustainable Manufacturing force to perceive matters related to technical equipment exploitation in a different way. [6, 8, 10, 11, 14, 21, 22, 24] The enterprises coordinate their actions in scope of product quality, high reliability, effectiveness of technical facilities and focus on keeping 100% safety in all production departments.

Therefore, to assure uninterrupted production continuity it is nowadays not sufficient enough to use only preventive actions but proactive, autonomous actions become standard. These actions utilize latest technical solutions that enable precise diagnostics and constant supervision over most critical elements of technical systems. The key element of these actions it to precisely define the range of planned maintenance and to define optimal exploitation timing.

Maintenance cost is getting higher and higher when compared to the percentage share in overall costs [17]. However, this cost should be examined as ratio between achieved benefits and incurred
expenditures [23]. Defining potential failure recovery time will make it possible not only to estimate possible financial effects and proper assessment of ratio between maintenance cost and achieved benefits but will also allow to minimize the cost through implementation of optimal preventive and proactive actions.

2. Problem description

Many maintenance departments in many different companies face a number of problems when it comes to planning and scheduling of preventive and proactive actions related to exploitation of technical systems. There are many obstacles when it comes to preparation of optimal plan such as:

- Number of technical equipment: machines, devices, network, drives, controls. The higher the number the greater need for: actions, records,…,
- diversity of technical systems: requiring greater knowledge, experience in scope of: electronics, hydraulics, pneumatics, automation. … Introduction of one of above mentioned elements, if it had not been present before e.g. hydraulics, will especially require additional trainings,
- lack of trainings that would keep up with technical development of machining floor and production automation in enterprises and with implementation of new management methods e.g. TPM or Lean Management,
- constraints:
  - physical – e.g. lack of sufficient number of employees
  - technical – e.g lack of sufficient resources in terms of diagnostics tools
  - system – e.g. inability to stop the production at any given time
  - legal – e.g. work conducted in defined time frame (e.g. 8 hours)
  - ekonomic-financial – e.g. lack of sufficient financial resources required to purchase spare parts

All above mentioned constraints and problems (and these not mentioned) force the maintenance team to continuously seek methods, tools, factors, recommendations that would improve their work and would enable to optimize management and scheduling of exploitation actions related to preventive tasks. Methods or tools that are under preparation should help in elimination or at least to minimize the effect of above mentioned constraints and problems.

Intention of authors is to draw up a method to support the actions of maintenance team, and especially in relation to:

- defining preventive and/or proactive actions based on estimated failure occurrence risk level,
- defining methods for preventive actions based on costs related with failure effects and duration time,
- setting preventive tasks related to all aspects of sustainable development.

When analysing different tools used in SUR actions, the authors focused their attention to FMEA method as starting point to undertake the works, suggesting modifying FMEA in order to use it to the benefit of maintenance team and to eliminate any inconveniences this document may carry.

3. Main advantages of FMEA method

One of the most frequently used tools that support technical service is FMEA analysis (Failure Mode and Effects Analysis). FMEA is a popular tool (especially in aerospace and automotive) used to analyse the root causes and effects of faults that occur in product, subassemblies or elements. This method is used in all places where it is important to find out the causal link, that means places where there is a necessity to systematically eliminate faults, flaws oraz any other risks and to effectively reduce the risk related thereto.

In reference to technical systems, thanks to application of FMEA method it is possible to [2, 3, 9, 24]:

1. identify and systematically, permanently eliminate causes of failure through recognition of true reasons of occurrence and through implementation of relevant preventive and corrective actions;
2. document machine and devices exploitation process and to apply the accumulated knowledge to plan the way of monitoring and diagnostics of technical measures;
3. analyse machine and devices exploitation process, and consequently introduce actions resulting in achieving better efficiency and durability, as well as modernization of machining floor based on received results;

4. create data base, where all the following information are stored:
   4.1. failure reasons and methods of recovery,
   4.2. undertaken corrective and preventive actions as well as their effectiveness,
   4.3. failure effects (downtime, defects) in reference to production, quality, safety or environment,
   4.4. level of spare parts use and their durability,
   4.5. estimated cost and downtime,

5. use collected information, data or analyses in correlation with operation and maintenance manual (DTR) to create optimal schedule of services, preventive or proactive tasks.

   All the control and preventive actions are to be planned in a correct way in order not to be too much of a burden for maintenance departments. Not only the failures but also the reasons for which the performance or quality has dropped are events for which preventive actions shall be applied. FMEA method may provide essential information [4, 5] so as to plan and performed exploitation actions resulted in as great as possible financial and organizational benefits in all service sectors of maintenance. FMEA method has also advantage of carrying out the analysis in field of:

   1. Planning, development, production, quality control, shipments, installation, exploitation and maintenance [7] in reference to production [12], safety and environment [15]
   2. Problem approach (in case of failure occurrence) and system approach (analyze of each components of technical equipment) [20, 24, 18]

3. Previous and future events and another analysis (update of actions) while the conditions change [16, 19]: process, technical, law, organizational or economical.

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4. Proposed modification of FMEA method

FMEA method, just like any other tools and methods has it faults. Following can be count among them:

- time-consuming and labour intensive
- imperfection of ranking model, especially when it comes to: scale, subjectivity, lack of repeatability and reproducibility, …
- lack of reliable mathematical model for the RPN factor (Risk Priority Number):
  - RPN value is identical to different ranking values S * O * D (Severity * Occurance * Detection),
  - exponential character of RPN value distribution for different values in ranking scale it means that value of RPN factor increases exponentially along with the scale,
  - setting optimal limit values of RPN factor to define corrective and preventive actions,
- lack of possibility to use cost and time scale for analysis

FMEA method was modified and improved many times. These modifications were dependant on the field they were used in: e.g.: environmental analysis EFMEA (environmental FMEA), fields of enterprise activity e.g.: system analysis SFMEA (system FMEA) and dependant on realized function as it was carried out in FMECA (Failure Mode and Criticality Analysis).

Taking as an example other modifications to FMEA method and recognizing the need of adopting it to analysis of preventive and proactive actions, following changes and modifications were proposed:

- Ranking scale has been changed from range of 1-10 to range of 1-7.
- RPN factor Risk Matrix has been replaced for risk level evaluation.
Adopting ranking scales to analyse maintenance activities, in accordance with three aspects of sustainable development

Replacing ranking scale “Occurrence” with scale of predicted duration of failure mode “Duration”

Suggested changes are presented in detail further in this study.

4.1. Change of ranking scale

Applying marks in scale of 1-10 is very subjective [1], which results in lack of repeatability and reproducibility when comparing the values from the scale with similar types of maintenance activities. Changes in ranking scale and the way of choosing the factor from the scale should improve the repeatability and reproducibility factor as assumed by the authors. Choice of scale with range of 1-7 allows creating a more precise ranking scale, enabling to define the key values: minimum, medium, and maximum value. Change of scale allows also introducing principle of “three steps”, which make it possible to read the values from the scale in such a way that the statistical error is lower than in “typical” 1-10 scale. It has been presented in the drawing No. 1 and table 1. Firstly, we compare ourselves with average scale value (4). Depending on the decision, we analyse the lower or upper part of scale, once again comparing it to the middle value of specific range (3 or 6). In that way we can define the position of new value on the scale through conducting following operation three times ,assessed value is lower, higher or equal the reference value. The method of designing the scale is shown in the table 1.

![Figure 1. Diagram „Choice of values from the ranking scale 1-7”](image)

| Grading scale | Scale description |
|---------------|-------------------|
| 7 max         | Very bad          |
| 6 < max       | Bad               |
| 5 > sr        | Fairly bad        |
| 4 sr = (max – min) /2 | Fair |
| 3 < sr        | Fairly good       |
| 2 > min       | Good              |
| 1 min         | Very good         |

4.2. Risk Matrix – failure mode risk assessment
Due to subjective character of Risk Priority Number (RPN) factor and its low precision, it seems that more effective way to define the risk level is to apply Risk Matrix. Risk Matrix allows to determine essential fields from the FMEA analysis point of view e.g.:

- green colour – no need to take actions
- yellow colour – taking actions is recommended but not necessary,
- red colour – actions are needed to reduce the risk.

This method of evaluating risk is less precise than RPN, but is much less subjective in its nature. Change by one or two places in the ranking scale does not influence the decision that much as it is the case when calculating RPN number. Area of uncertainty in the risk assessment is essential in the matrix only at the border of tolerance limits, therefore tolerance lines should be defined by team of experts so as to avoid in some way the occurrence of type I and type II errors.

Example of risk matrix are shown in the figure 2 and 3. It should be noted that it is possible to design risk matrix with 2-stage as well as 3-stage scale. In case of 3-stage scale, in the staging area (marked with yellow) it is the team that decides whether the actions are necessary to be taken and what would be the scope of actions.

**Figure 2.** Example of risk matrix in 2-stage scale.

**Figure 3.** Example of risk matrix in 3-stage scale.
5. Ranking charts

Essential element of FMEA method is definition of corresponding ranking charts: effects, frequency of occurrence and detection (appropriately: severity (S), occurrence (O), detection (D)). In reference to the cause of failure (maintenance event (ZO)), the effect in the FMEA analysis does not refer only to one aspect e.g. impact on production, but it is also related with safety and environment. Therefore reviewing the effects of ZO should be related to all three aspects of sustainable development. In the table’s 2, 3, and 4 examples of ranking charts in the aspect of production are shown: severity for production, duration of maintenance event, detection of maintenance event.

| S   | Production                                                                 |
|-----|---------------------------------------------------------------------------|
| 7   | Production stoppage                                                        |
| 6   | Process stoppage                                                          |
| 5   | Machine stoppage                                                          |
| 4   | Change in quality level of large number of products                       |
| 3   | Change in product quality level                                           |
| 2   | Impact on production capacity                                             |
| 1   | No impact                                                                |

Table 2. Ranking chart – severity for production.

| D   | Duration                                                                 |
|-----|---------------------------------------------------------------------------|
| 7   | Threat of contract termination                                             |
| 6   | Threat to delivery date                                                    |
| 5   | Change of target date                                                      |
| 4   | Production plan replaced                                                    |
| 3   | Shift in production plan                                                    |
| 2   | Shifting production to other machine                                       |
| 1   | Possible during machine operating time                                     |

Table 3. Ranking chart – duration of maintenance event.

| D   | Detection                                                                 |
|-----|---------------------------------------------------------------------------|
| 7   | Not able to detect                                                        |
| 6   | Monitoring or diagnostics                                                 |
| 5   | Not detected by technician                                                 |
| 4   | Not detected by operator                                                   |
| 3   | Detected by technician                                                     |
| 2   | Detected by operator                                                       |
| 1   | Able to detect in all instances 100%                                       |

Table 4. Ranking chart – detection of maintenance event.

Legitimacy of using the ranking chart in reference to ZO effects shall not be questioned as the results of the root cause are vital elements of failure analysis. In accordance with the principle of sustainable development not only production severity should be important but effects on safety and environment should be taken into consideration as well. However, in the authors’ opinion only when reviewing all three aspects at the same time gives the whole picture of risks resulting from causes and effects. As a consequence it allows estimating risk of: costs and downtime.
In the tables 5 and 6 examples of ranking charts for safety and environment are presented.

**Table 5.** Ranking chart for safety aspect.

| S | Safety                  |
|---|-------------------------|
| 7 | External threat to life |
| 6 | Danger to life          |
| 5 | Health loss             |
| 4 | Health hazard           |
| 3 | Inconvenience in the workplace |
| 2 | Discomfort in the workplace |
| 1 | No impact               |

**Table 6.** Ranking chart for environmental aspect.

| E | Environment             |
|---|-------------------------|
| 7 | External environmental risk |
| 6 | Internal environmental risk |
| 5 | Negative impact on the environment |
| 4 | Media loss              |
| 3 | Excessive consumption of media |
| 2 | Increased consumption of media |
| 1 | No impact on environment |

Detection ranking chart (DT) has special meaning in the field of preventive actions, since it allows to define methods and tools preventing from unplanned occurrence of maintenance event (ZO) e.g.: diagnostics, monitoring. Value of this factor has influence on preventive actions (e.g. autonomous actions) in scope of: organization, measures and resources of maintenance department.

6. **Duration – maintenance event**

Estimation of risk in FMEA for occurrence brings some doubts in case of using this method by maintenance team. It is related with different point of view between production department and maintenance team (SUR) on issue of failure occurrence. From the maintenance team (UR) point of view the frequency of failure occurrence is essential. Calculation of MTBF factor for specific subassembly would allow to precisely defining the time frame in which preventive actions should be taken. From the technical point of view it is very hard to reliably estimate the time between failures of single component. In reference to specific assembly that failed, defining that kind of factor is not that obvious – failures of the same assemblies do not have to occur frequently enough to gather statistical results. Reliability of assembly is influenced by a number of other conditions e.g.: using spare parts from different suppliers.

The knowledge on which subassembly caused the failure is not of great importance to production departments – production stoppage or reduction of capacity are essential facts [13]. Also the reason for stoppage is not that important for these departments. Even the frequency of maintenance events (ZO) is less important than duration of ZO (described e.g. by MTTR (Mean Time to Repair)). More frequently occurring but instantly recovered failures have different importance than one long stoppage that greatly influences the production schedule. Therefore, in the opinion of the authors, duration factor (DU) is more reliable than occurrence. Duration has also significant influence on all of the aspects: production, safety, and environment. Duration of maintenance event is significant also cost wise. The longer duration of failure the higher costs related thereto. In many cases cost increases exponentially.
7. Method verification
In order to verify the method of one of the production facilities in medical business the experiment has been carried out. Experiment covered:
1. Appointing team, that will carry out the analysis
2. Choice of machine for analysis
3. Defining ranking charts and determining tolerances of risk matrix
4. Conducting analysis and making comparison with the history of maintenance events
5. Preparation of conclusion and usage of gathered information to correct the preventive plans.

8. Appointing team
After agreeing with the company management, following team was formed:
- 1 maintenance department manager
- 2 foremen
- 2 mechanics
- 2 electricians
- 1 parts warehouse employee
- 1 logistics employee
- 1 purchasing employee

Team is represented by persons directly engaged in maintenance tasks. Many years of experience of these employees guarantee diligent and reliable analysis. 6 out of 10 employees directly took part in servicing the chosen machine.

9. Machine selection
In order to carry out analysis following machine was selected: IPC-Z002 – Rotary heat sealing machine DVT (drawing No.4). It is a 6-year old machine working in 2 shifts. Machine documentation contains all the information related to exploitation: electrical and pneumatic diagrams, services and maintenance timing as well as spare parts specification. The history of maintenance events covers years 2014 – 2017. During this period following was recorded:
- 44 Failures,
- 46 Defects,
- 48 Adjustments,
- 16 Services,
- 16 Diagnostics actions,
- 508 Set-ups,
- 64 Other actions.

Figure 4. IPC-Z002 – Rotary heat sealing machine.
10. Defining ranking charts and determining tolerances for risk matrix

The team defined ranking charts in accordance with the principles of sustainable development keeping the guidelines from point 4.1 – principle of three steps. The borders of tolerance for the risk matrix were defined in a similar way. The team chose variant for scale with three fields. Three matrixes were defined connecting production, safety and environmental aspect with duration of maintenance event. Ranking charts and risk matrixes were subject to verification after analysis had been carried out by the team.

11. Conducting analysis and comparison with the history of maintenance events

The team carried out analysis for maintenance events in 3 stages:
- I stage covered: failures, defects and adjustments
- II stage covered: services and regulations
- III stage covered: set-ups and other actions

Analysis has been carried out for whole machine with division into: drive module, sealing module, electrical system, pneumatic installation, auxiliary equipment.

The team during analysis has modified ranking charts 3 times and corrected tolerance borders in the risk matrix 2 times. After changing the ranking charts and correcting the tolerance borders in the risk matrix analysis has been retrospectively revised.

| Requirement | Potential maintenance event | Potential effect - Production | Potential effect - Safety | Potential effect - Environment | Potential causes of failure | Predicted duration of failure mode | Chance of failure detection | RPM | Proposal of preventive actions |
|--------------|-----------------------------|-------------------------------|--------------------------|-------------------------------|---------------------------|----------------------------------|-----------------------------|-----|--------------------------------|
| Damaged matrix | 5 | 1 | 2 | Damaged electrode | 3 | 2 | Checking the status of electrodes by operator at the beginning of each shift and reporting to DT department if needed |
| Sealing matrix | 5 | 1 | 2 | Deterioration of electrodes | 3 | 2 | Checking the status of electrodes by operator at the beginning of each shift and reporting to DT department if needed |
| Dirt on the matrix | 5 | 1 | 2 | Dirt on the upper matrix | 3 | 2 | Checking the status of electrodes by operator at the beginning of each shift and reporting to DT department if needed |
| Lack of power supply | 5 | 1 | 1 | No impact | 3 | 2 | Checking the status of electrodes by operator at the beginning of each shift and reporting to DT department if needed |

Figure 5. Excerpt from FMEA with conducted analysis.

12. Compilation of results and utilization of gathered data to correct the preventive plans

Based on carried out analysis a report was made that included:
1. Description of advantages and disadvantages of the method
2. Comparison of analysis results to history of maintenance events
3. Utilization of gathered information to correct the preventive plans and preventive action schedules

The team defined following advantages while using the method:
- Simplified definition of ranking charts: adding border points (min, max) in the ranking table simplified its definition. However, team also made some minor mistakes, which were corrected during the analysis and after its completion. This situation was related to special cases (e.g. in the ranking table referring to maintenance event duration scale D=2 and D=3 were merged together as number D=3, and time for scale D=2 changed its name to: possible in the maintenance shutdown.
- Simplified definition of risk analysis: using the reference point allowed to determine risk analysis more precisely.
Higher repeatability during risk analysis: in 3 cases it appeared that team analysing similar possible root cause of maintenance event gave the same mark to all of these cases,

- Additional benefits resulting from merging 3 aspects of sustainable development: mainly related to safety, since it was not taken into consideration that accurately in past analyses. Due to analysis of environmental aspect it was possible to define a few environmental risks,

- Time required to carry out analysis was reduced by ca. 25%. Specifying ranking charts and risk matrixes more precisely would probably shorten this time even more. The team noticed that if analysis was to be used with different technical objects, the effectiveness of this method would increase even more.

- Following disadvantages were noticed:
  - Problem with setting the tolerance borders when defining risk matrix
  - Team noticed the necessity of adding one more ranking chart related with the cost of maintenance event covering not only downtime but also cost of additional parts, labour and service works.

  Additional introduction of mechanisms that would allow verification of maintenance plans based on the maintenance events. Such mechanisms would make it easier to implement corrective actions to existing entries in maintenance plans. It was also pointed that there is a need for transferring the method to computer software with possibility of creating “cause, effect and preventive action tree”.

  Comparison of results of the analysis with the history of maintenance events allowed to come to following conclusions and to introduce corections to former preventive action plans:
  - Analysis allowed to “detecting” 93% of maintenance events. Analysis was carried out in a time constraint that influenced the effectiveness of the method,

  23 cases of possible maintenance events were “detected”, that were not taken into consideration in the former preventive plans, out of which: 12 were related to safety, 7 related to environment and 4 were related with production

  - Due to optimization of preventive plans, 31 entries that simplified the procedure of conducting the preventive actions were corrected e.g.: owing to change in order of conducting tasks it was possible to shorten their completion time by 15 min.

13. Conclusions

There are many methods and tools enabling successful maintenance management. During last few decades attitude in this field required many changes. Choice of right method for maintenance management in reference to used technical infrastructure in the company is a fundamental element that influences its reliability, durability and effectiveness of actions by maintenance team (SUR). In reference to technical systems, with the use of FMEA method it is possible to identify and systematically, permanently eliminate the root cause of failure through undertaking optimal preventive and proactive actions.

Suggested modifications to FMEA method such as: change of ranking scale, replacing the RPN factor with risk matrix, considering the effects on production, safety and environment make it possible to use the modified FMEA method by the maintenance team (SUR).

Use of above mentioned changes will allow to define fields of risk affected by smaller errors, and as a consequence make it possible to define actual corrective and preventive actions for specific: threat effects, their duration and ability to detect them. Therefore, based on above mentioned it will be possible to create more effective preventive and proactive actions, and by using the techniques taken out from the quality management (i.e. applying service and frequent verification of analyses through: consideration of new maintenance events (ZÓ), new machines and devices, design and technical changes), we will make it possible to improve actions in all fields and aspects of maintenance.

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