APPLICATION OF FMEA-FTA IN RELIABILITY-CENTERED MAINTENANCE PLANNING

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ABSTRACT

The failure mode and effects analysis (FMEA) has been used in identifying and reducing risks of failures in systems, equipment, and components following a bottom-up approach. The technique has been criticized for being unintuitive and cumbersome. The fault tree analysis (FTA) follows a top-down approach to identifying the root causes of failures. We apply FMEA to a large-sized axial plunger pump in an Egyptian fertilizers production plant. We extend the analysis to using the FMEA outcomes to launch the FTA to support the evaluation of the potential failures modes. We argue that the two techniques; FMEA and FTA, can complement each other in support of equipment reliability and availability studies. Together, they can offer as the basis of a reliability-centered maintenance planning, a systematic means of cataloguing information about potential failures, and accumulation of better knowledge of potential problems and improvement actions besides possible maintenance cost reductions.

KEY WORDS

FMEA, FTA, RCM

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1. INTRODUCTION

Reliability is vital for production and all industrial systems. Reliability implies that a system would not fail. Yet, the possibility of failure cannot be dismissed. Consequently, an effective failure modes analysis approach is necessary in designing and planning the operation of a reliable system. Identifying preventive maintenance requirements for developing reliable systems and components is referred to reliability-centered maintenance (RCM). RCM consists of two tasks: first is to analyze failure modes and their effects on the performance of the system. The second task is the evaluation of the impact of the maintenance schedules on the reliability of the system. FMEA identifies and prioritize failure modes and their effects and levels of severity. Based on that, maintenance decisions are made [1, 2]. The failure mode and effects analysis (FMEA) and the fault tree analysis (FTA) are two common approaches in that regard. FMEA [3 – 5] is a qualitative approach that is used to identify and investigate potential system weaknesses and rank those using risk index named the Risk Priority Number (RPN). The FMEA process advances as depicted in Fig. 1.

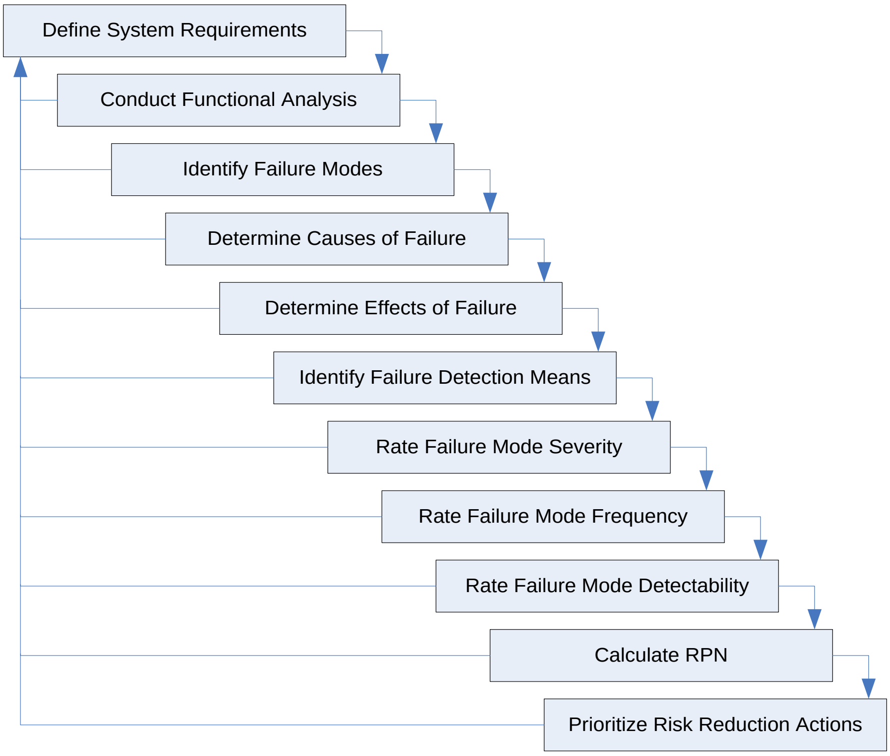

Fig. 1. Generic FMEA process

Corrective actions and provisions can then be proposed to reduce the likelihood of the occurring. The FMEA employs a bottom-up approach. Starting at the component level for each subsystem, the analyst determines how the device or part might fail and what would be the effects and consequences of such a failure on the component and all other interacting components. The consequences of each identified failure mode are then classified according to its severity. FMEA can be applied to process or a product; that is functional or physical entities .

When FMEA is extended by criticality analysis procedures of the failure modes classification, the method is called failure mode effects and criticality analysis or FMECA. The criticality analysis prioritizes the failures for corrective action based on the possibility of the item's failure mode and the severity of its effect. It uses linguistic terms to rank the likelihood of the failure mode occurrence, the severity of its effect and the potential of the failure getting detected, on a numeric scale from 1 to 10. Those three rankings make up the RPN value. When applying FMEA, a cross functional and multidisciplinary team identifies failure modes, evaluates their risks and prioritizes them so that appropriate corrective actions can be taken. The overall outcome is enhancing the reliability of the system and/or the product and reducing costs.

The FTA is a deductive approach that graphically enumerates and analyzes the different ways in which a particular failure mode can occur and the probability of its occurrence. FTA is applied to specific failure modes. A separate fault tree is developed for each critical failure mode. It is structured in the form of a tree, using several symbols to represent three (top, intermediate, and basic) levels of events and Boolean logical relationships. FTA is normally used to discover the root causes of failures through, systematically, determining what would happen to the system if the status of a part in it is altered. A fault tree is developed by tracing out and analyzing the chains of faults for each event, until a basic fault level (e.g., specific component or human error) is reached. Probabilities are then assigned to the various basic faults or errors. This enables probabilities for the various failures to be estimated, and their relative contribution to total risk assessed. In theory, the failure modes with the highest probabilities are addressed first. When used correctly, FTA yields a measure of risk from interrelated chains of events and an estimate of uncertainty [3, 4].

FMEA and FTA are two commonly used reliability analysis techniques. FTA is relatively a quantitative method offering measures of risk and uncertainty. FMEA, on the other hand, is relatively qualitative approach. In this paper, we use FTA to support FMEA applied to a large-sized axial plunger pump in an Egyptian fertilizers production plant. We show how FTA can help overcome some FMEA shortcomings. We believe that the two analysis approaches can effectively complement each other in performing the equipment reliability and availability assessment. Together, they can offer a systematic means of accumulating and cataloging information about potential failures and their causes and inter-relationships.

2. LITERATURE REVIEW

FMEA and FTA have been widely used in reliability analysis for decades. A state of the art review of FMEA applications was published in Bouti and Kadi [6]. We are not aware of any more recent surveys. Yet, FMEA's applications since 1960s have been diverse. A good review of FMEA applications is in Shauhan et al. [7]. Researchers also discussed certain potential drawbacks with FMEA and suggested modifications; in particular with respect to quantification of the risk priorities. The methodology has also been criticized for being unintuitive and cumbersome due to too many of the many-to-many relationships among failure modes, effects, causes, etc. In Seyed-Hosseini et al. [8] the RPN is modified to involve the indirect relationships among the risks and the failure consequences. Narayanzgounder and Gurusami [9] also suggested a new prioritization of failure modes based on the ANOVA analysis that was used to compare the means of the RPN values rather than using their simple values. The issue was also addressed in Shauhan et al. [7]. Some researchers have used other analysis tools in support of FMEA. Korayem and Iravani [10] used the quality function deployment (QFD) to support the FMEA analysis and classification process by identifying the important system characteristics (from QFD) and help guide the allocation of resources suggested by FMEA.

Applications of RCM for industrial pumps have been published. A framework for applying FMEA to enhance RCM for pumps was discussed in Azadeh et al. [1]. They attempted to customize a system that focuses on centrifugal pumps. Thus they seem to suggest developing customized FMEA frameworks for the various areas of applications. They argued that it is usually difficult to deal with pump failures with precise mathematical analysis, particularly in complex industrial systems. Besides diagnosis done by human operators is time consuming and it is as effective as the accumulated experiences of the analysis team members. Ebrahimipour et al. [11] also applied FMEA to enhance pump reliability. The case study presented in the next section describes using FMEA and FTA for RCM planning of an industrial pump in an Egyptian fertilizers plant (Abo Qir Fertilizers).

3. A CASE STUDY

The equipment being studied is the axial plunger pumps of the ammonia plant of the Abu Qir Fertilizers Company- Egypt. Ammonia plants are huge complex processes (See Fig. 2). Abo Qir plant produces 1,100 tons of ammonia per day. The objective is to define the operating ranges for each of the operating parameters, and the operating hours of the plunger pump for chemical plant, with regard to the Piping and Instrumentation Diagram (P&ID) of the ammonia plant. Based on the plunger pump datasheet, maintenance history, and the interpretation of the field expert maintenance personnel, the preferred, allowable, minimum downtimes, minimum spare parts and maximum performance efficiency of the pump.

Fig. 2. Ammonia plant

The axial plunger pump is a reciprocating pump that uses a plunger to move media through a cylindrical chamber. The plunger is actuated by electric drive. Plunger pumps use a cylindrical mechanism to create a reciprocating motion along an axis, which then builds pressure in a cylinder or working barrel to force gas or fluid through the pump. The pressure in the chamber actuates the valves at both the suction and discharge points. The capacity of the plunger pumps can be calculated with the area of the piston or plunger, the number of pistons or plungers, the displacement of the stroke, and the speed of the drive. The power from the drive is proportional to the capacity of the pump. Seals are an integral part of piston pumps and plunger pumps to separate the power fluid from the media that is being pumped. A stuffing box or packing is used to seal the joint between the vessel where the media is transferred and the plunger or piston. A stuffing box may be composed of bushings, packing or seal rings, and a gland.

3.1 The FMEA Procedure

The standard FMEA process evaluates failure modes for severity (S), occurrence (O), and detection (D) each on a scale from 1 to 10. The product of these values results in what is known as the risk priority number (RPN). Let severity rate be S, occurrence O, and detection D, then the RPN is given by: $RPN = S \times O \times D$, and the criticality assessment: $Criticality = S \times O$.

The RPN is a measure of design risk. This value may be used to roughly rank order the concerns in the design. The RPN value is in the range of 1 to 1000. In employing FMEA as a continuous improvement tool, the analysis team should undertake efforts to reduce the high RPN values risk through the appropriate corrective actions. In general practice, regardless of the result of the RPN analysis, special attention should be given when Severity is high (9 or 10). The RPN can then be used to compare issues within the analysis and to prioritize problems for corrective action.

Figure 3 shows the general procedure of the FMEA process followed in this work. The first phase of the process includes information gathering to the calculation of the RPN. The actions in the second phase contain the ranking of RPNs, the recommendation of corrective actions, and the modifications of the design when appropriate. At the end of the procedure, a FMEA report can be obtained, and the required modifications are completed to reduce the number of the potential failure modes to the minimum [12 – 14]. During the work, the absence of documentations and data records was a huge problem that made data collection a tedious task. Equipment manuals, failure reports, and operations logbooks were the primary sources used.

3.2 Results

In Table 1, a description of the system functions is presented. The Table shows the failure modes, failure causes and failure effects for the pump main components (pump motor, stuffing box packing, oil tank, oil filter, crank shaft oil seal, bearing, gear box and valves).

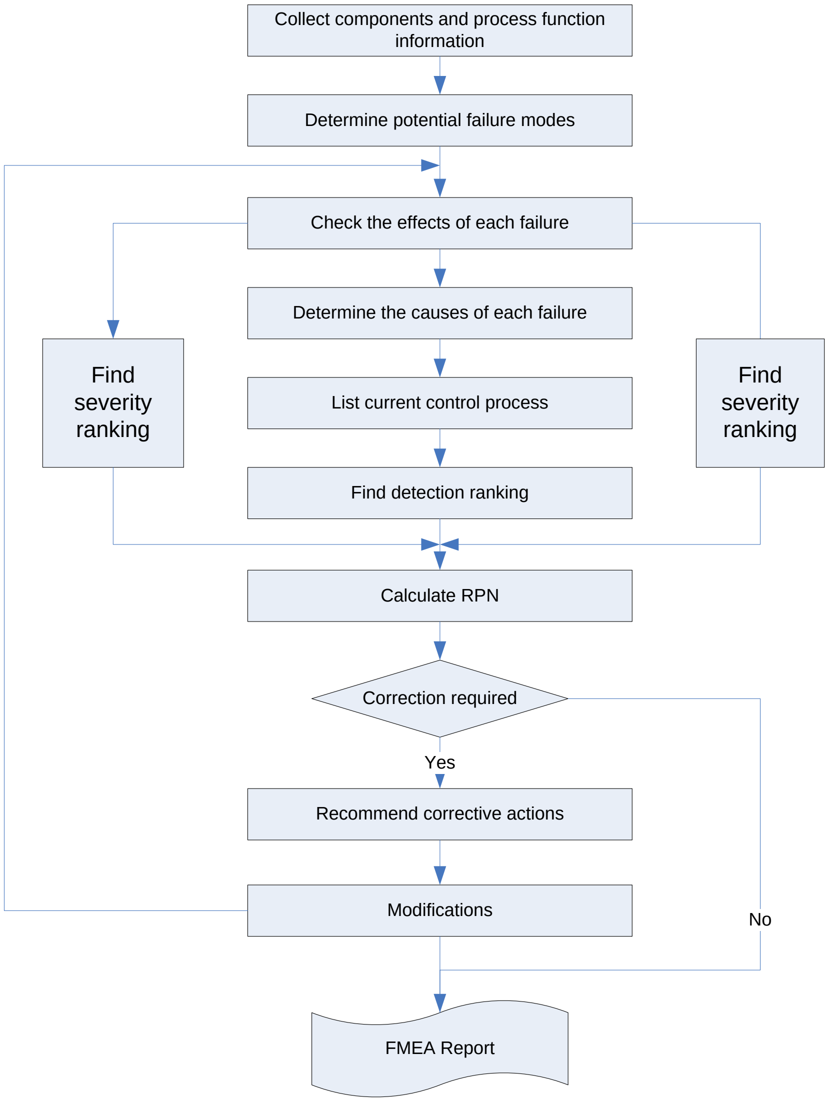

Fig. 3. The FMEA procedure

In Table 2, FMEA punctuation form is presented. The calculated RPN values and criticality for the failure modes are presented. It can be observed that the RPN for worn motor bearing, seal leakage and gearbox high vibration are 72, 36, 84, respectively. Also, the vibration of the pump gear box is the highest criticality value of failure modes. Table 2 shows the form of FMEA punctuation for the lubrication and cooling system of the motor and pump bearings, reduction gear system, and the pump. The criteria for failure modes evaluation ratings are given in Table 3, for severity, occurrences and detection. Four levels of detection were adequate in our application.

After the FMEA use, an analysis is done using FTA for the vibration of the pump gear box. The fault tree of the general failures in the oil system is given in Fig. 4. It shows the failure causes in the main components (cooling system, oil tank and filter for the gear box oil cycle for the pump.

Table1 . Description of system functions, failures and effects

System Identification					
Function	**Description of system function**				
Component	**Component Function**	**Functional Failure**	**Failure Mode**	**Failure Cause**	**Failure Effect**
1. Pump motor	Rotate the pump shaft	1.1 Do not pump start	Overload	Overheating	Pump shutdown and system shutdown
		1.2 Pump rotation incorrect	Pump rotation incorrect	Phase sequence incorrect	Pump shutdown and system shutdown
		1.3 Worn motor bearing	Pump trip	High vibration	Pump trip and system trip
2. Stuffing box	Seals	2.1 Leakage	Low pressure	Defect of peaking	Pump low performance efficiency
3. Oil tank	Lubricting rotating parts	3.1 Oil low pressure	Bearing high temperature	Oil low level	Pump trip and system trip
4. Filter	Filter the oil	4.1 Do not filter the oil	Deterioration	Disruption of the filter mesh	Risk of contaminating oil load with residues
		4.2 Obstruct oil flow	Clogging High differential pressure	Excess of impurities in filter element	Consignment in the system lubrication and cooling
5. Crank shaft oil	Seals the oil	5.1 Prevention the oil Leakage	Oil leak	Worn crankcase oil seals	Shutdown of the pump.
6. Bearing	Crankshaft support	6.1 vibration	Knocking noise	Broken or worn bearing.	Pump trip very high vibration
7. Pump nozzle	Pumping	7.1 Low pressure	Low pressure	Worn nozzle.	Delivery pressure decreases and system low efficiency
8. Gear box	Reduction the speed	8.1 High vibration	Noise	Imbalance	Pump trip very high vibration
9. Suction valve	Isolate system components and supervision and control accessories	9.1 Do not isolate supervision and control accessories	Leakage	Head valve or opposed head valve deterioration	Impossibility to execute maintenance in the supervision and control accessories
		9.2 Improperly isolate the supervision and control accessories		Valve piston stiff	Risk of accident
10. Discharge valve	Isolate system components and supervision and control accessories	10.1 Do not isolate supervision and control accessories	Leakage	Head valve or opposed head valve deterioration	Impossibility to execute maintenance in the supervision and control accessories
		10.2 Improperly isolate the supervision and control accessories		Valve piston stiff	Risk of accident

Table 2 . FMEA punctuation form

Failure Id.	1.1	1.2	1.3	2.1	3.1	4.1	4.2	5.1	6.1	7.1	8.1	9.1	9.2	10.1	10.2
Severity	2	3	6	6	2	1	2	2	7	3	7	1	1	2	2
Occurrence	3	2	3	3	2	1	1	1	1	2	3	2	2	2	2
Detection	1	3	4	2	2	2	2	3	3	2	4	2	2	2	2
RPN	6	18	72	36	8	2	4	6	21	12	84	4	4	8	8
Criticality	6	6	18	18	4	1	2	2	7	6	21	2	2	4	4

Table 3. Criteria for failure modes rating

Severity		Occurrence	
1	Very insignificant effect, corrected immediately by the operation team	1	Without failure registry in the last 2 years.
2	Insignificant effect, corrected immediately by the maintenance team.	2	1 failure in the last 2 years.
3	Minor effect, the component suffers to a gradual degradation case is not repaired.	3	2 failures in the last 2 years.
4	Moderate effect, the pump component does not execute its function, but the failure does not provoke **trip** in the pump unit and its maintenance does not demand stop of pump.	4	3 failures in the last 2 years.
5	Moderate effect, which does not provoke **trip** actuation in the pump unit, but whose maintenance demands stop of pump.	5	4 failures in the last 2 years.
6	Moderate effect, which provokes **trip** actuation in the pump unit and whose maintenance demands stop of pump during one day or less.	6	5 failures in the last 2 years.
7	Critical effect that provokes **trip** actuation in the generating unit and whose maintenance demands stop of pump for more than one day.	7	6 failures in the last 2 years.
8	Very critical effect that provokes **trip** actuation in the generating unit and brusquely interrupts the system functions.	8	7 or 8 failures in the last 2 years.
9	Very critical effect that provokes **blackout** actuation in the generating units and collapse of the process.	9	9 failures in the last 2 years.
10	Catastrophic effect that can cause damages to pump main components or people.	10	10 or more failures in the last 2 year.
Detection			
1	Failure indicated directly by the instrumentation devices.		
2	Failure identified by the team operation daily inspections.		
3	Failure identified for abnormal noises, or indirectly by the instrumentation devices.		
4	Occult failure, impossible to be identified by the operator.		

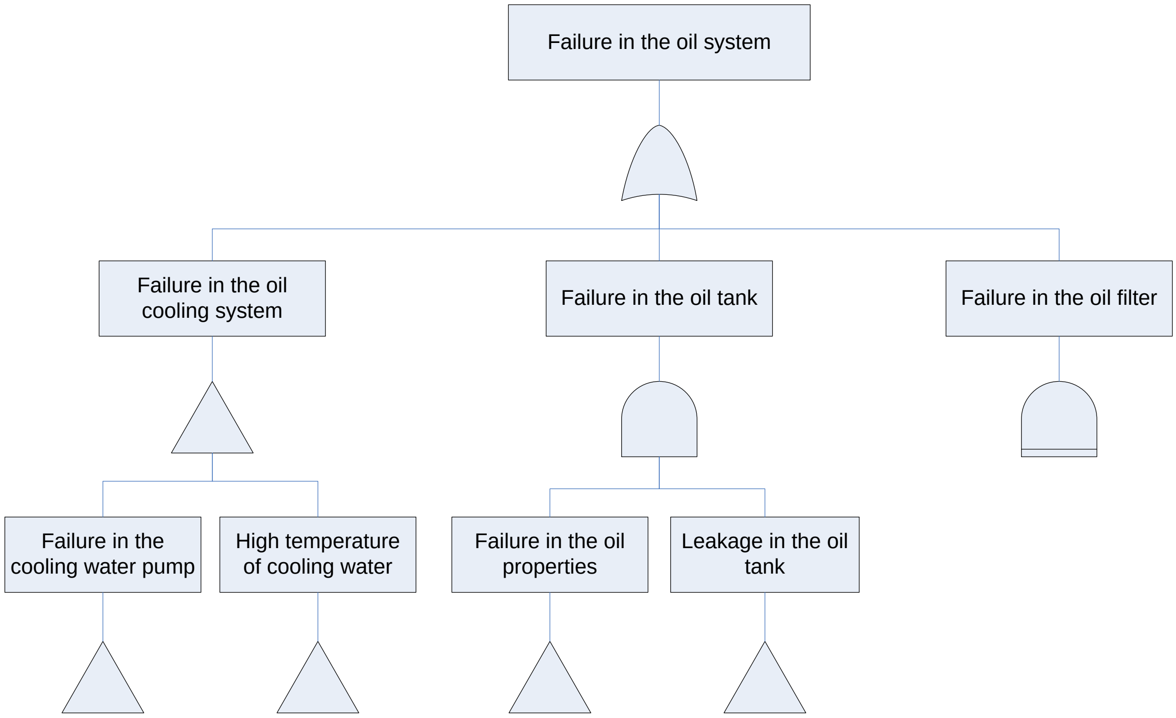

Fig. 4. FTA of the general failure in the oil system

4. DISCUSSION AND CONCLUSIONS

In the present work, FMEA-FTA analysis in support of reliability-centered maintenance planning has been conducted. The FMEA results indicate that the critical components of the system are the gear box pumps command and oil cycle. This result comes from the relatively high severity of the failures in these components. The failures of the gear box pumps can make their automatic commutation impracticable, which can cause the pump to stop for insufficient oil outflow, very low oil level in the oil tank or high temperature. These two cited failures are considered severe and must be prioritized in an eventual decision-taking about maintenance if reliability is to be achieved. However, these two above-mentioned equipment, gear box and oil cycle for plunger pump, are in redundancy, as it can be observed in the fault tree. So, the probability that failures in these equipment affect the rest of the system is much reduced.

The FTA identifies as critical the components of the lubrication and cooling system on the combined bearing for plunger pumps, and the heat exchangers and the command circuits of the motors as well. The heat exchangers, however, does not lead to severe failure but they are frequent. It is observed that FTA does not consider the severity of the failures, but only the occurrence. Therefore, when a FTA is developed, the top event must be selected carefully, in a way that all the basic events can be considered, in a certain form, severe.

It can be concluded that the two techniques, FMEA and FTA, have complementary importance for the evaluation of potential failures in the plunger pump. They propitiate the objective analysis for justifying system changes, analyzing common failure modes and assuring attendance to the security requirements. It is recommended that the two techniques be combined for a more complete RCM study and planning.

The use of FMEA and FTA in the current application provided a systematic means of more reliable data and information collection and analysis about the system failures, basis for improvement in the system using the properly monitored data, possibility of reducing total maintenance costs through the failure-occurrence prevention, and promoting the attitude of failure prevention rather than fixing failures. The analysis done using FTA and FMEA should lead to the elaboration of a plan of action to establish an RCM culture.

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