Paper Machine Breakdown Reduction by FMEA and Preventive Maintenance Improvement: A Case Study

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Abstract. FMEA is a widely selected tool for the application of machinery breakdown prevention. This research adopted FMEA technique to reduce and prevent the breakdown of the important equipment of a large commercial paper machine that has capacity of 200,000 tonnes per annum located in the Northeast area of Thailand. This research accomplished the improvement of preventive maintenance in other machines for rapid implementation and improved machine inspections. After implementation, the downtime of paper machine belonging to maintenance department responsibility reduced significantly 5 hours per month by average, machine availability, OEE, and MTBF increased 0.46%, 0.51%, and 10 hours respectively. The machine downtime has been on the downward trend.

1. Introduction

In the present, pulp and paper industry has high competition [1-2]. To make the company profitable, stay competitive, survive in the global marketplace, companies need to improve and find the way to develop to excellence continuously to promote the success and sustainable growth of the company in the long run. Many companies around the world including studied pulp and paper mill experienced machine breakdown problems [3-4]. The problems lead to losses of production opportunity, repairing costs and product quality costs resulting in the rising production cost.

PM1 paper machine is the paper machine with 200,000 TPA (Tonnes Per Annum) of capacity located on one of the largest pulp and paper mills in Thailand. It started producing commercial paper in 2008. In the past three years, PM1 suffered from many breakdown problems which impacted production volume, production costs and made maintenance costs higher. So this paper focused on breakdown reduction of PM1 paper machine.

Failure Mode and Effect Analysis (FMEA) is an effective and accepted tool in the application to prevent or reduce the breakdown problems of many machines. It considers potential failure modes, causes of failure mode and effects and represents the risk in the RPN (Risk Priority Number) form which can be determined by the product of Severity (S), Occurrence (O) and Detection (D). Once the risk assessment is done, the next step is to find corrective or preventive actions to cope with causes of failure or failure mode. After that, the RPN will be re-calculated.
FMEA was found to be successfully used in both aerospace and automobile industries for enhancing manufacturing reliability of product [5]. It was widely accepted and implemented later in many businesses in the application of maintenance field. FMEA was applied to reduce failure of boiler in sugar mill [6] and improve the reliability of wind turbine system [7]. With the application of the suitable FMEA software package to 2 MW wind turbine, the reliability of generator and gearbox increased. H R Feili et al applied FMEA to identify failure risk of Geothermal Power Plants (GPPs) [8]. K Cieck et al applied FMEA in concepts to identify possible risks of failure of vessel oil system [9]. Moreover, FMEA was used to improve the reliability of thin-film transistor liquid crystal display products [10]. E Runsa et al used FMEA as a tool in the application of developing computerized preventive maintenance management system for CNC machine. After improvement and implementation, the availability, quality rate, and performance rate increased significantly, resulting in the increase of OEE [11]. S Tangjitsitcharoen et al also successfully applied FMEA techniques to new elevator for preventive maintenance improvement. The countermeasures to failure causes and failure mode resulted in the reduction of a number of failures and the increment of MTBF [12].

The purpose of this study is mainly to apply FMEA technique along with the improvement of preventive maintenance and machine inspection to reduce PM1 paper machine breakdown loss time belonging to maintenance department responsibility.

2. Problem identification
This paper summarized the breakdown of the PM1 paper machine from January 2017 to December 2017. The Pareto diagram was based on the equipment type to determine the type of machine to be improved and focused on.

![Pareto diagram of PM1 paper machine breakdown loss time](image)

*Figure 1. Pareto diagram of PM1 paper machine breakdown loss time*

It can be seen from the picture 1 that 80% of breakdown loss time occurred with 17 types of equipment. According to the 80/20 rule of pareto diagram, all the 17 types were selected to be improved for breakdown loss time reduction. The Soft Calender roll and Drying cylinder roll are found to be very chronically problematic thus are important and the solution is more difficult than others, so FMEA is a way to find actions to prevent breakdowns and proper maintenance plans. Most of the problems found on other machines can be easily solved by creating new preventive maintenance plans.
3. Methodology
This research applied FMEA to Soft Calender roll and Drying Cylinder roll and improved preventive maintenance for other equipment with the following steps:
1. Review production processes and machines.
2. Brainstorm for the possible failure modes of machine and potential effects.
3. Identify possible cause of failure and assign severity, occurrence, and detection criteria.
4. Evaluate risk priority number (RPN).
5. Identify corrective or preventive actions to cope with failure causes or failure modes.
6. Assess risk priority number (RPN) after actions
7. Revise preventive maintenance programs for other equipment

4. Failure mode and effect analysis of Soft Calender roll and Drying Cylinder roll

4.1. Criteria for assessing RPN
The criterion for assessing RPN was determined by expert team at the studied mill and the agreement with the production department.

4.1.1. Criteria for severity assessment. This criterion is mostly based on the paper machine downtimes occurring in this paper mill. The severity criterion is shown in the table 1.

| Effect                      | Severity Criteria                                                                 | Rank |
|-----------------------------|-----------------------------------------------------------------------------------|------|
| Hazardous without warning   | Very high severity ranking - affects operator, plant or maintenance personnel and safety and/or effects non-compliance with government regulations without warning. | 10   |
| Hazardous with warning      | High severity ranking - affects operator, plant or maintenance personnel and safety and/or effects non-compliance with government regulations with warning. | 9    |
| Very high                   | Downtime more than 8 hours.                                                      | 8    |
| High                        | Downtime between 4 hours and 8 hours.                                             | 7    |
| Moderate                    | Downtime between 1 hour and 4 hours.                                              | 6    |
| Low                         | Downtime between 30 minutes and 1 hour.                                           | 5    |
| Very low                    | Downtime up to 30 minutes                                                        | 4    |
| Minor effect                | Process parameters variability exceeds upper/lower control limits; adjustments or process controls need to be taken. No downtime and no defective parts. | 3    |
| Very minor                  | Process parameters variability within upper/lower control limits; adjustments or process controls need to be taken. No downtime and no defective parts. | 2    |
| None                        | Process parameters variability within upper/lower control limits; adjustments or process controls not needed or can be taken between shifts or during normal maintenance. No defective parts. | 1    |

4.1.2. Criteria for occurrence assessment. It is the criteria for the assessment to find chance that it may occur. It used the data from the past to present to apply in such assessment.

For example, the problem of sensor malfunction causes the machine to order the paper to be cut, which usually occurs 2 times a month by average so in this case the MTBF of sensor is 2 weeks. In another case, the failure of Drying Cylinder roll’s bearing occurred every 8 years by average, so the MTBF of this bearing was about 8 years or 416 weeks.

The criterion for occurrence assessment is shown in the table 2.
Table 2. Occurrence criteria for FMEA

| Probability of Failure Occurrence | Possible Failure Rates Criteria | Rank |
|----------------------------------|---------------------------------|------|
| Very high: Failure is almost inevitable | MTBF less than 2 weeks | 10   |
| High: Repeated failures | MTBF between 2 and 4 weeks | 9    |
| MTBF between 5 and 12 weeks | 8     |
| Moderate: Occasional failures | MTBF between 13 and 24 weeks | 7    |
| MTBF between 25 and 52 weeks | 6     |
| MTBF between 25 and 104 weeks | 5     |
| MTBF between 105 and 208 weeks | 4     |
| Low: Relatively few failures | MTBF between 209 and 312 weeks | 3    |
| MTBF between 313 and 520 weeks | 2     |
| Remote: Failure unlikely | MTBF greater than 520 weeks | 1    |

4.1.3. Criteria for detection assessment. In the preparation of the detection criteria, we considered the ability to detect the failure of the machine, equipment or parts before the machine malfunction or breakdown. In case where the failure of the machine is difficult to be detected, the score will be high, such as the visually examination of the A53 carbon steel pipe that transports water may be unable to identify whether the pipe is damaged, or whether the pipe thickness still in an acceptable value or not so the score is high unlike the use of Ultrasonic Thickness Measurement or X-ray to inspect the pipe or sealing weld. In case if the failure detection of equipment or parts of the machine are relatively simple, the score is less. For example, a detection of bearing failure on a rotating machine with 3,000 cycles per minute of speed by using a vibration analyser that can analyse the spectrum when combines with severity level, it can identify whether the bearing is damaged or not so the score in this case is quite low.

Table 3. Detection criteria for FMEA

| Detection | Detection Criteria                                                                 | Rank |
|-----------|-----------------------------------------------------------------------------------|------|
| Extremely Unlikely | Machinery controls or inspections cannot detect a potential cause and subsequent failure, or there is no machinery inspections | 9    |
| Low Likelihood | Low chance that machinery inspections will early detect a potential cause and subsequent failure mode before the machinery functional failure occurs. | 7    |
| Medium Likelihood | Medium chance that machinery inspections will early detect a potential cause and subsequent failure mode before the machinery functional failure occurs. Machinery controls will prevent imminent failure. | 5    |
| High | High chance that machinery inspections will early detect a potential cause and subsequent failure mode before the machinery functional failure occurs. Machinery controls will prevent an imminent failure and isolate the cause. | 3    |
| Almost Certain | Machinery controls or inspections almost certain to detect a potential cause and subsequent failure mode before the machinery functional failure occurs. | 1    |

4.2. FMEA result
As the calendar section and dryer section comprised of many machines/equipment, this paper represented only the analysis of soft calendar roll which was shown in the table 4.
| Possible Failure Mode(s) | Potential Failure Effect(s) | S | Possible Failure Cause(s) | O | Current Failure Prevention(s)/Detection Method(s) | D | R | P | N | Recommended Action(s) |
|------------------------|-----------------------------|---|--------------------------|---|-----------------------------------------------|---|---|---|---|-----------------------|
| High Vibration         | PM1 may shutdown            | 7 | Defective or damaged roll bearing | 3 | - Vibration analysis - Oil analysis           | 1M | 3 | 63 | - Vibration analysis/Oil analysis - Check plain bearing conditions - Replace plain bearing - Check roller bearing conditions | 1M/3M | 7 | 2 | 3 | 42 |
|                       |                             | 6 | Bearing housing hold-down bolt looseness | 2 | - Vibration analysis - Check bolts/Tighten all bolts | 1M | 3 | 36 | - Vibration analysis/Check loose bolts - Tighten all bolts | 1M/3Y | 6 | 2 | 3 | 36 |
| Bearing Failure        | PM1 must shutdown           | 7 | Roll misalignment | 3 | - Vibration analysis | 1M | 5 | 105 | - Vibration analysis/Roll alignment | 1M/3Y | 7 | 7 | 2 | 32 |
| Abnormal roll surface wear | PM1 may shutdown           | 7 | Roll misalignment | 3 | - Vibration analysis | 1M | 5 | 105 | - Vibration analysis/Roll alignment | 1M/3Y | 7 | 7 | 2 | 32 |
| Poor Paper Quality     | PM1 may shutdown            | 7 | Roll misalignment | 3 | - The same as in high vibration case | 1M | 5 | 105 | - Vibration analysis/Roll alignment - The same as in high vibration case | 1M/3Y | 7 | 7 | 2 | 32 |
|                       |                             | 5 | Spurious oil pressure | 8 | Online oil pressure monitoring | 1 | 40 | - Calibrate and service pressure transmitter - Control valve overhaul | 1Y | 5 | 0 | 12 |
|                       |                             | 5 | Defective DPR | 5 | - Check DPR | 3M | 3 | 90 | - Check DPR/DPR overhaul | 3M/1Y | 6 | 4 | 1 | 24 |
|                       |                             | 7 | Worn/damaged longitudinal seals or end seals | 2 | - Check seal conditions - Check directional valve | 3M | 3 | 42 | - Check seal conditions/Replace seals | 3M/3Y | 7 | 2 | 3 | 42 |
|                       |                             | 6 | Hydraulic cylinder leakage | 5 | - Check hydraulic cylinder conditions | 2W | 1 | 9 | - Check conditions/Replace hydraulic cylinder - Visual Inspection | 1D/2Y | 6 | 4 | 3 | 72 |
|                       |                             | 7 | Motor burnt | 4 | - Check motor temperature - Check motor current - Vibration analysis - Clean motor externally | 1M | 5 | 120 | - Check motor current/Check temperature - Vibration analysis/Check voltage balance - Clean motor/Leak to ground test - Open check terminal box and clean - Check, clean and tighten all electrical connections - Motor overhaul and electrical testing | 1M/3M | 6 | 3 | 5 | 90 |

Table 4. FMEA result of Soft Calender roll
After analysing possible failure mode, potential effect and possible failure cause, risk assessment was performed in the form of RPN. This research mainly reduced the risk of failure mode caused by failure cause with RPN greater than 100. This figure was agreed by mill expert team. After evaluating the RPN, the action was determined. After implementing actions, the RPN was subsequently assessed and found to be reduced.

5. Improvement of preventive maintenance programs for general equipment and inspections
Because PM1 is a large paper machine and consists of a large number of smaller machines, the FMEA is done only in the most important and problematic areas, namely the Calender section and the Dryer section. Others can be easily improved by creating and revising the PM plans. Equipment that needed preventive maintenance improvement was mainly equipment that produced the breakdown loss time according to the Pareto diagram in Figure 1 and other equipment to prevent breakdown.

The equipment/machines that were improved in preventive maintenance tasks and plans were shown in the table 5.

| No. | Equipment for PM Improvement |
|-----|-----------------------------|
| 1   | Control valve               |
| 2   | Rolls                       |
| 3   | Stretcher                   |
| 4   | Variable speed drive        |
| 5   | Electric motor              |
| 6   | Sensor                      |
| 7   | Belt                        |
| 8   | Heat exchanger              |
| 9   | Fibron conveyor             |
| 10  | Hydraulics                  |
| 11  | Screw pump                  |
| 12  | Universal joint             |
| 13  | Level transmitter           |
| 14  | Filter                      |
| 15  | Tail cutter                 |
| 16  | Vacuum pump                 |
| 17  | Gear reducer                |
| 18  | Fan/Blower                  |
| 19  | Multi-stage pump            |
| 20  | Switchgear                  |

In addition to improving the preventive maintenance tasks and plans, improvement of the inspection of the machine was also done. In the past, machine inspection was done every 2 weeks for each type of machine with unclear inspection order and inspection route. As described, there was one inspection sheet for each type of the machine, but the machines are scattered throughout the mill thus making inspection route very far. After the improvement, the machinery inspection route was divided into two routes and many types of machines were examined orderly in the same inspection sheet to minimize the distance of the inspection. Moreover, the new inspection is risk-based inspection. Frequency of the inspection was revised from the traditional inspection performed every two weeks to daily inspection, weekly, bi-weekly, and monthly inspection as machine ranking and risk of failure. More than 25,000 inspection items per month were increased and more basic inspection tools were deployed thus making machine inspection more effective and better.

6. Implementation of actions from FMEA and preventive maintenance improvement
In May 2018, planned shutdown of the paper machine was performed to improve and maintain according to the plans. There were replacement of new plain bearings and Differential Pressure Regulator (DPR) of Soft Calender roll, change of Soft Calendar roll and pressure transmitter. Moreover there was roll alignment checking for soft calendar roll during this shutdown. The maintenance of Drying Cylinder roll and the maintenance according to the improved preventive maintenance plans were performed as well. Furthermore, there were corrections of machine abnormalities found on the inspection of the machine and from the notice of the production department.
In addition, a new inspection pattern was introduced in early May 2018 with the introduction of a new inspection sheet to inspect machines daily, weekly, bi-weekly and monthly. Moreover, the old inspection sheets and plans for some types of machines that were not revised in inspection tasks were increased of the frequency from two weeks to one week per month.

![Figure 2. 200,000 TPA PM1 paper machine](image)

![Figure 3. Soft Calender roll changing during planned shutdown of May 2018.](image)

![Figure 4. Calendar roll alignment checking](image)

![Figure 5. Dryer steam joint services](image)

7. Result
After implementation of actions from FMEA, starting preventive maintenance according to the revised maintenance plan, and new inspections, it appears that the breakdown loss time of the paper machine between before improvement and after improvement, the breakdown loss time decreased significantly as shown in the table 6. The availability, OEE, and MTBF of PM1 paper machine in the three months following the improvement are also increased as shown in the table 7 below.

| Table 6. Breakdown loss time comparison |
|----------------------------------------|
| **Period** | **Breakdowns (Hrs.)** | **After Improvement (107 Days)** | **Period** | **Breakdowns (Hrs.)** |
| 16-28 Feb. 2018 | 60 | 1-30 Jun. 2018 | 52 |
| 1-31 Mar. 2018 | 21 | 1-31 Jul. 2018 | 35 |
| 1-30 Apr. 2018 | 37 | 1-31 Aug. 2018 | 13 |
| 1-31 May 2018 | 57 | 1-15 Sep. 2018 | 11 |
Table 7. Availability, OEE and MTBF comparison

| Month      | Before Improvement | After Improvement |
|------------|--------------------|-------------------|
| A (%)      | OEE (%)            | MTBF (Hrs.)       | A (%)      | OEE (%)            | MTBF (Hrs.)       |
| Mar’18     | 91.17%             | 83.04%            | 32         | 86.33%             | 76.82%            | 28         |
| Apr’18     | 87.72%             | 79.48%            | 14         | 88.74%             | 81.34%            | 30         |
| May’18     | 87.89%             | 78.21%            | 27         | 92.91%             | 83.95%            | 35         |
| Three Months | 88.95%             | 80.26%            | 21         | 89.41%             | 80.77%            | 31         |

Table 8. Percentage of difference of OEE and MTBF

|                      | OEE     | MTBF   |
|----------------------|---------|--------|
| Before Improvement   | 80.26%  | 21 Hrs.|
| After Improvement    | 80.77%  | 31 Hrs.|
| Difference            | 0.51%   | 10 Hrs.|
| Percent of Difference | 0.64%   | 47.6%  |

8. Conclusion

This research accomplished the application of FMEA technique to the PM1 paper machine in dryer and calendar section, the creation and revision of preventive maintenance for both mechanical and electrical equipment and the improvement of machine inspections. After implementation, the PM1 breakdown loss time that belongs to maintenance department responsibility was reduced by 5 hours per month from 38 hours on average during the three months prior to improvement from March to May 2018, down to 33 hours on average over the period of 3 months after improvement. The availability increased 0.46% from 88.95% to 89.41%, the OEE increased 0.51% from 80.26 % to 80.77% and the MTBF increased 10 hours from 21 to 31 hours.

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