Maintenance Optimization in Process Plant Using Failure Mode Effect Analysis

Prabhu R. Gohil, Hitesh Purohit, Madhusudan Achari, Shebaz A. Memon

***Abstract*— Experimental investigations are conducted to assess the influence of various equipment in terms of MTBF (Mean time between failures) and MTTR (Mean Time To Repair) in this study. Analysis of these data has helped to find out the critical components in the coil and mill Plant at Anjar, Kutch, India. The goal of this work is to analyze the maintenance data and recommend an optimized maintenance plan. The genetic algorithm is proposed as a heuristic search method for maintenance optimization in Plate and coil mill plant units. The genetic algorithm searches for the best solution for the efficiency enhancement of the plant. This paper presents the use of genetic algorithms in maintenance optimization in Plate and coil mill plants. Failure mode effect analysis is the used methodology in the proposed work which is a fundamental piece of the specialized plan of support to enhance framework quality and hence lessens costs related to upkeep that is utilized as a part of a wide range industry.**

***Index Terms*—Maintenance engineering, Maintenance management, Predictive maintenance, Preventive maintenance, Condition monitoring, FMEA (Failure modes and effects analysis), GA (Genetic Algorithm)**

I. Introduction

Increasing competition has brought the profit levels of industries to wafer-thin levels [1]. This has increased the efforts on cost-cutting measures including on the maintenance budget of machines in the process and manufacturing industries [2]. The modern trend in management is to look at maintenance as an opportunity investment area instead of seeing it as an expense [3]. Apart from that, the breakdown of machines due to insufficient maintenance has other consequences[4]. It leads to the late delivery of the product, a rise in the cost of the product, and an effect on the reputation of the concerned industry among other things [5]. This necessitates closer scrutiny of maintenance processes [6] and provisions for better maintenance practices [7].

In this study, the detailed analysis of maintenance and breakdown data of several years of the process plant is carried out by using Failure mode effect analysis. This has led to a better idea of the breakdown probability of different machines. The analyzed data is then used to arrive at an optimum maintenance schedule using the Genetic Algorithm.

II. PROBLEM FORMULATION

The industry had maximum problems with maintenance at the plate & coil mill. So, in the plate & coil mill plant, the objective is to find critical components and suggest an optimized maintenance plan for those components. The present work focuses on evaluating critical component maintenance by executing failure modes and effects analysis [8]. It also focuses on executing a genetic algorithm for better optimization for maximum plant availability [9].

The Basic maintenance parameter [10] which is usually considered in the optimization of maintenance operations is the availability of the plant. The operational availability of the plant (Ao) can generally be represented by the two terms: 1) Mean time between failures (MTBF), and 2) Mean downtime (MDT). The Inherent availability of the plant (Ai) can generally be represented by the two terms 1) Mean time between failure (MTBF) and 2) Mean time between repairs (MTTR)

As a part of the case study plate & coil mill in Welspun Pvt Ltd. is selected. In the plate & coil mill plant, historical data is collected with the information of Delay, MTTR, and MTBF. After analyzing the data, some critical components of the plant are found [11], which need more care to be taken while planning maintenance given below:

- Reheating furnace (RHF)
- Steckel mill coiler furnace (SMCF)
- Descaler
- Downcoiler.

Plant breakdown data were collected for 6 months for effective maintenance analysis.

Data Collection steps:

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- Historical maintenance records study
- Monthly Plant breakdown data collection
- Experts, supervisors, and laborers' observations compilation, and brainstorming to study the causes of failures and their downtime.

Data Analysis steps:

- An organization of the maintenance database for effective and simplified data analysis.
- Inspection of maintenance data for critical equipment availability measurements.
- Identification of critical Components and their failure causes which cause the frequent breakdown of the plant.
- Analysis of the number of failures and resulting downtime of the plant.
- Analysis of Operational and Inherent Availability of the plant.
- Study on the interdependency of critical equipment breakdown on the overall downtime of the Plate & Coil mill plant

In this study, an analysis was done for the maintenance data collected from the historical database and breakdown-maintenance records. A cause-and-effect relationship was found between maintenance activities and production output. Critical equipment was selected and analyzed to simplify the complex system as it helps in focusing on critical maintenance issues. The causes for the failure, its effective downtime, and the number of failures were focused on evaluating the effects on the availability of the Plate & Coil mill plant.

Table 1Maintenance breakdown data of critical components

Month	Total time (hrs)	Uptime (hrs)	Downtime (hrs)	No of failures	MTBF (hrs)
Jun	720	686	34	11	62
Jul	744	693	51	24	29
Aug	744	709	35	11	64
Sep	720	689	31	10	69
Oct	744	716	28	9	80
Nov	720	691	29	9	77
Dec	744	701	43	21	33
Jan	744	703	41	21	33

Table 1 shows the real-time data collection at the Plate & Coil Mill plant from Jun to Jan to analyze the availability of the Plate & Coil Mill plant. The collected breakdown data were inspected to calculate maintenance parameters i.e. mean time between failures (MTBF), Mean time to repair (MTTR), mean downtime (MDT), Operational availability, and Inherent availability.

Table 2 Availability calculation of critical components

Month	Downtime frequency	MDT	MTTR	Operational Availability	Inherent Availability
Jun	0.0160	3.0909	0.9273	0.9528	0.9853
Jul	0.0346	2.1250	0.6375	0.9315	0.9784
Aug	0.0155	3.1818	0.9545	0.9530	0.9854
Sep	0.0145	3.1000	0.9300	0.9569	0.9867
Oct	0.0126	3.1111	0.9333	0.9624	0.9884
Nov	0.0130	3.2222	0.9667	0.9597	0.9876
Dec	0.0300	2.0476	0.6143	0.9422	0.9819
Jan	0.0299	1.9524	0.5857	0.9449	0.9828

Table 2 shows the availability calculation of critical components and Table 3 downtime data of critical components. four critical components are selected for the study. The above data were selected for the said critical components, i.e. Downcoiler, Reheating furnace, Descaler, and Steckel mill coiler furnace. Critical failures were observed which caused frequent breakdowns in the plate & coil mill plant. Critical failures were analyzed month-wise.

Table 3 Downtime data of critical components

Month	Down time (total)	Downtime (Downcoiler)	Downtime (RHF)	Downtime (Descaler)	Downtime (SMCF)
Jun	34	8	12	9	5
Jul	51	30	15	0	6
Aug	35	14	3	10	8
Sep	31	8	9	6	8
Oct	28	9	8	5	6
Nov	29	7	9	6	7
Dec	43	20	12	3	8
Jan	41	14	10	7	10
Total	292	110	78	46	58

Figure 1 shows the critical component's number of failures percentage-wise. From Figure 1, It is observed that the downcoiler (38%) has frequent failures, and other components have approximately.

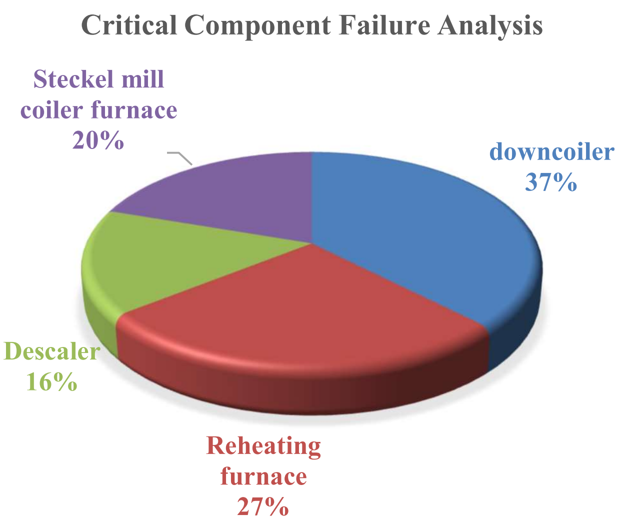

Figure 1 Critical Component Failure Analysis

At the Plate & Coil mill plant, Plant downtime was observed due to the breakdowns. Frequent failures in equipment lead to an increase in overall plant downtime. The Plate & Coil mill plant is located in series and all the critical equipment are working in series, any failure at any critical equipment affects the overall running time of the plant.

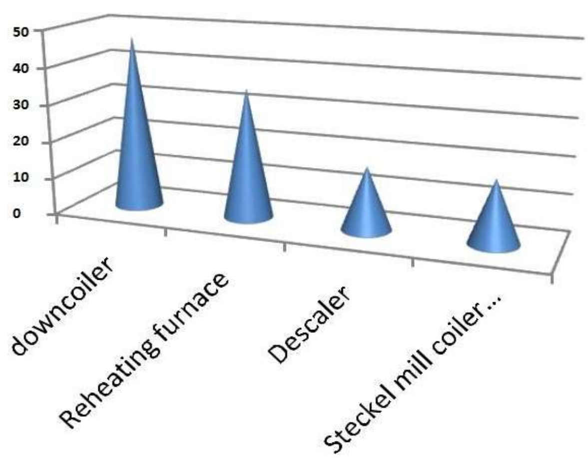

Figure 2 Downtime (hrs) analysis

Figure 2 represents the downtime of the critical components. It is observed that downtime for the Downcoiler is maximum due to frequent failures at the downcoiler. It is important to note that critical equipment are interdependent on one another hence any failure of any equipment leads to an increase in the overall downtime of the Plate & Coil mill plant. Thus it is of supreme importance to analyze the failure causes that lead breakdown to in the plant. Here, the downcoiler is the most critical equipment as it has the maximum number of failures and high downtime in comparison to the other critical equipment at the Plate & Coil mill plant.

From Figure 3, It is observed that in the Plate & Coil mill plant critical component's operational availability for June to January. The average operational availability is approximately 95% per month. It can be seen that in October the operational availability reached a maximum of 96.5% due to the yearly preventive maintenance schedule in the said month. It is noted that the operational availability of the said critical component of the Plate & Coil mill plant is between 93%- 95% approximately in the rest of the months. Thus, it can be concluded that operational availability is decreasing even after preventive maintenance also which needs an improved maintenance optimization program. The reduced operational availability results in loss of production and enhancement of production and maintenance costs.

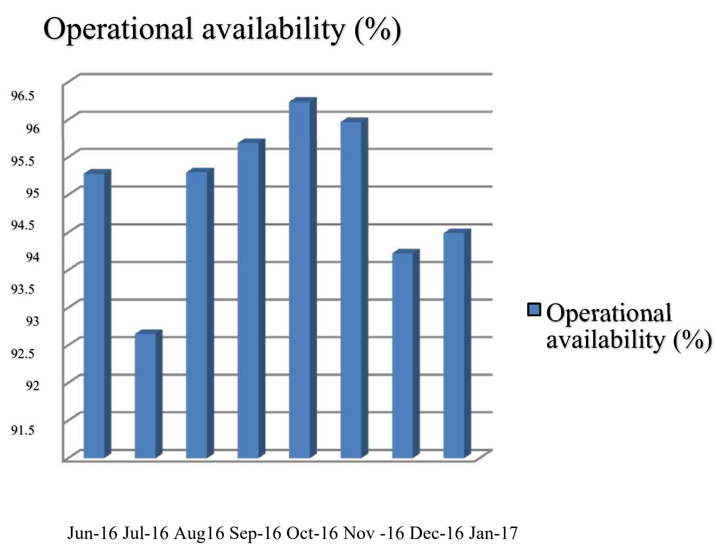

Figure 3 Operational availability analysis

The graph Figure 4 represents the reliability bathtub curve for the study. The Bathtub curve is a plot of the failure rate of a product versus its operating life (time). Three types of failures exist according to a failure that occurred during a product's operating life and accordingly, the bathtub curve is divided into three phases.

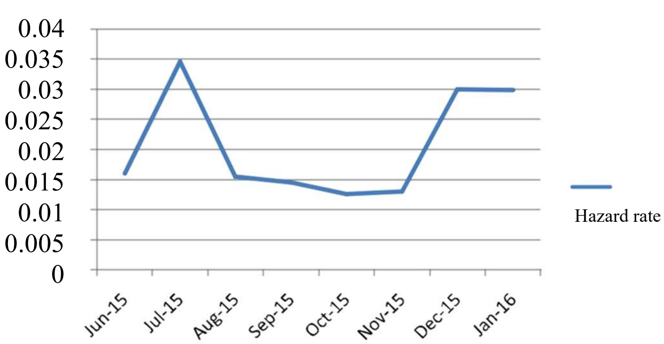

Figure 4 Reliability bath curve

Phase 1- "Break in or start-up" period of bathtub curve (June

2015 –August 2015) wherein the failure rate is decreasing and the items become less likely to fail as their survival time increases.

Phase 2- "Useful" life (September 2015-November 2015) wherein the failure rate becomes nearly constant, (In this period, the failure rate is lowest and nearly constant). The useful life period is the most common time frame for making reliability predictions.

Phase 3- Wear-out (December-January) wherein the failure rate increases due to the wearing out of critical parts with the wearing out of the critical parts, it takes less stress to cause system failure. The overall system failure rate increases.

Table 4 shows that the average availability of the four components should be 98.72%. But Table 2 shows that the operational availability of said components ranges between 93%-96% even after the high individual operational availability of the critical components as shown in Table 4.

Table 4 Availability calculation of particular critical components

Sr no	Critical components	Operational availability
1	Downcoiler	98.18%
2	Reheating furnace	98.54%
3	Descaler	99.08%
4	Steckel mill coiler furnace	99.16%
Average operational availability at the plant		98.72%

Hence after this analysis, it can be concluded that the Plate & Coil Mill plant operational availability is interdependent to critical components performance and breakdown. I.e. if it is calculated individually then the Downcoiler operational availability is low (98.18%) and the Steckel mill coiler furnace operational availability is high (99.16%), however, the end operational availability of Steckel mill coiler furnace will be counted as 98.18% only as all the components working in series and their operations are interdependent to each other performance and breakdown. So in case of any failure in any of the critical components, the whole plant will suffer a breakdown and production will stop till it is repaired.

III. FMEA (FAILURE MODES AND EFFECT ANALYSIS)

FMEA is a methodology designed to identify potential failure modes for a product or process[12], assess the risk associated with those failure modes, rank the issues in terms of importance, and address the most serious concerns to carry out corrective actions [13].

In general, FMEA requires the identification of the following basic information as shown in Appendix I:

- Items
- Functions
- Failures
- Effect of failures
- Causes of failure
- Current control
- Other relevant details

Basic analysis procedure of FMEA:

- Assemble the team.
- Institute the basic rules.
- Collect and review relevant information.
- Identify the items to be analyzed.
- Identify the functions, causes, effects, and control for each item to be analyzed.
- Assess the risk associated with its tangible evaluation with the issues identified.
- Prioritize and assign corrective actions.
- Perform corrective actions and re-evaluate risk.
- Distribute, review, and update the analysis, as appropriate.

Basic FMEA models are[14] briefly described in Table 5 and Table 6.

Table 5 Chances of failure

Rank	Chances of failure	Description	Probability
1	Unlikely	Unreasonable to expect this failure mode to occur.	1/100000
2	Isolated	Based on similar designs having a low number of failures.	1/10000
3	Sporadic	Based on similar designs that have experienced occasional failures.	1/1000
4	Conceivable	Based on similar designs that have caused problems.	1/100
5	Recurrent	Certain that failures will ensue.	1/25

Table 6 Maintainability probabilities

Rank	Maintainability criteria	Description	The Probability of equipment in good condition
1	Very easy	Very easy to keep the equipment in good condition and spare parts are available for any failure.	0.8-1.0
2	Easy	Easy to keep the equipment in good condition and spare parts are available for any failure.	0.6-0.8
3	Moderate	Moderate probability of keeping the equipment in good condition and spare parts are less available.	0.4-0.6
4	critical	Tough to keep the equipment in good condition and spare parts are rarely available for any failure.	0.2-0.4
5	Very tough	Very tough to keep the equipment in good condition and spare parts are not available for any failure.	0.0-0.2

Selection of maintenance strategy will be made based on the type failure pattern as per Table 7.

Table 7 Selection criteria for Maintenance program

Rank	Maintenance Technique	Criteria
1	Predictive maintenance	RPN > 100
2	Preventive maintenance	50 < RPN < 100
3	Corrective maintenance	RPN <50

IV. CAD-BASED SOFTWARE MODELLING

MATLAB is a software package for high-performance numerical computation, visualization, and programming. The name MATLAB stands for MATrix LABoratory. It provides an interactive environment with numerous built-in functions for technical computation, graphics, and animation. It also provides simple extensibility with its high-level programming language.

Direct programming (coding) in MATLAB can be done either using the command window or creating a new script file/ function file (.m file). Using MATLAB, the data can be analyzed. Algorithms can be developed to create models and applications. The language, tools, and built-in math functions enable us to explore multiple approaches and reach a solution faster compared to spreadsheets or traditional programming languages.

Many types of optimization problems [15] can be solved by choosing the method that best suits the problem. The Optimization Toolbox and the recently released Genetic Algorithm and Direct Search Toolbox together provide a diverse set of methods that solve a variety of optimization problems.

The optimization problem formulated in this study is single-objective multivariable optimization using Genetic Algorithm (GA). The examination of the mathematical model developed indicates that the problem formulated in operational availability and inherent availability is mostly carried out based on uptime, downtime, and no of failures, wherein causes of failures and their effect on respective downtime are to be optimized.

For the same, the exact solution is not possible[16] in running a plant, and the practical point of view is not that significant. Efforts have been made to obtain the most optimized availability under the lower bound and upper bound ranges imposed by a practical situation in the running plant.

In the proposed work, the problem formulation consists of a single objective multivariable problem [17]. Conventional methods for said problem formulation are not efficient tools to solve such kinds of problems in which optimum availability is to be founded on the number of failures in critical components. GA works with the coding of the solution set and not with the solution itself. Almost all conventional optimization techniques search from a single point but GA always operates on a whole population of points. It improves the chances of reaching the global optimum and also helps in avoiding the local stationary point.

A. *Problem Formulation*

The Basic maintenance parameter that is usually considered in the optimization of maintenance operations is the availability of the plant.

1. The operational availability of the plant (Ao) can generally be represented by the two terms;
- Mean time between failures (MTBF)
- Mean down time

2. The Inherent availability of the plant (Ai) can generally be represented by the two terms;
- Mean time between failures (MTBF)
- Mean time between repairs (MTTR)

Upper bounds (ub) and Lower bounds (lb) are the ranges of the variables in Genetic algorithm terminology. Which are selected to define the ranges of the variables. The possibilities of occurrence of no. of failures in one month were defined as shown in Table 8 and Table 9 as several variables. i.e. {A,B,C,D,E} – lb (2,2,1,0,1), ub(10,7,6,5,3).

Table 8 Summary of Breakdown Data/Month

Sr no	Critical Component	Causes of failure	No of failures	Duration in hrs/failure
1	Downcoiler	Strapping	A	3
2		Improper	B	4
3	Reheating furnace	Position Control	C	3
4	Descaler	Leakage in	D	2

5	Steckel mill coiler furnace	Bottom pinch roll bended	E	5

B. Mathematical Modeling of Availability Parameters:

Operational Availability is the function of MTBF and MDT.

Ao = MTBF/ (MDT + MTBF)

Inherent Availability is the function of MTBF and MTTR.

Ai = MTBF/ (MTBF+MTTR)

MTBF = Uptime / No. of failures

MDT = Downtime / No. of failures,

MTTR = 0.3*MDT

Calculation for one month,

- MDT = (3A+4B+3C+2D+5E)/ (A+B+C+D+E)
- MTBF = {30*24 – (3A+4B+3C+2D+5E)}/ (A+B+C+D+E)}
- MTTR = 0.3*MDT
- Ao = MTBF/ (MTBF+MDT)
- Ai = MTBF/ (MTBF+MTTR)
- Where, lower bound and upper bound for (A, B, C, D, E) are (2,1,1,0,1) and (9,7,6,5,3)

Ao= [30*24 – (3A+4B+3C+2D+5E)] / (A+B+C+D+E)}]/ {[30*24 – (3A+4B+3C+2D+5E)] / (A+B+C+D+E)}] + [(3A+4B+3C+2D+5E) / (A+B+C+D+E)]}

Ai=[30*24 (3A+4B+3C+2D+5E)]/(A+B+C+D+E)}]/{30*24– (3A+4B+3C+2D+5E)] /(A+B+C+D+E)}]+{0.3*[(3A+4B+3C+2D+5E)/(A+B+C+D+E)]}}

Table 9 Causes of failure with possible no. of failures

No	Causes of failure	Possible no of failures in one month	Duration in hrs/failure
1	Strapping machine misalignment (A)	2-9	3
2	Improper lubrication (B)	1-7	4
3	Position Control valve damaged (C)	1-6	3
4	Leakage in the hose (D)	0-5	2
5	Bottom pinch roll bent (E)	1-3	5

C. Results from the MATLAB Programme

As discussed earlier, the plant availability is a function of mean uptime, mean downtime, and mean time between two failures. These functions are mostly treated as a repair function only, where the causes of failures and the number of failures are generally ignored. So, source code and program are developed in MATLAB for operational availability .m files are used for program run. The results for operational availability are given in Figure 5.

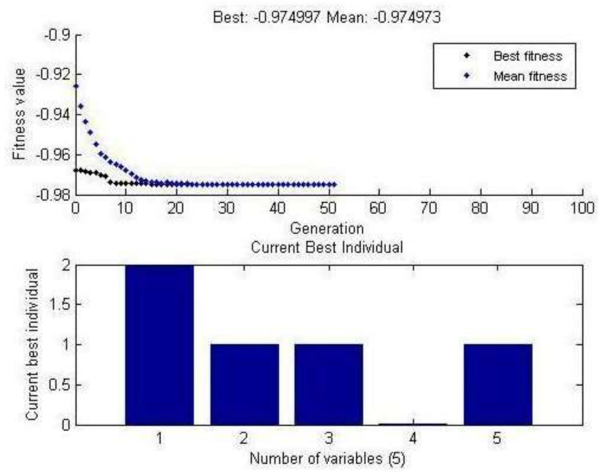

Figure 5 Operational Availability Optimization

As seen from the result in Figure 5, to obtain 97.5% operational availability, the value of D should be zero, which means that these causes for failures must be eliminated. The value of B, C, and E should be one and A should be two.

D. Result Comparison and Validation

Real-time data were collected and analyzed for plant availability. Remedial suggestions were made to improve plant availability. It is expected that by implementing the proposed remedial suggestion, the number of failures and the mean downtime can be effectively reduced. Ultimately, the uptime of the overall plant efficiency can be enhanced. The operational availability can be enhanced by 3-4.5% by implementing the corrective actions for the critical equipment.

Separate Programme code was developed in MATLAB software by considering operational availability and inherent availability as an objective function. The results show that operational availability of up to 97.5% and inherent availability of up to 99.23% can be achieved. The said results can be achieved by implementing the optimized value of variables, obtained by GA solver analysis.

V. CONCLUSION

Maintenance optimization is the basic necessity[18] of the industry which needs continuous monitoring of breakdown causes and their downtime. Plant availability optimization is one of the effective maintenance tools that can help to optimize the maintenance processes.

The GA technique used for optimization purposes provides an efficient and promising tool. Plant availability plays a significant role in overall equipment efficiency and hence, the determination has been a subject of interest for a long time. It is a single-objective optimization problem. The objective function is to optimize availability functions, MTBF, and MTTR by considering the upper bounds and lower bounds of variables. The variables are the number of failures and downtime, which is difficult to be solved by conventional maintenance methods. The main goal of the present work is to show the effectiveness of the proposed optimization methodology. This research work opens up new opportunities to carry out similar studies of bigger systems. The proposed work for maintenance operations seems to be reliable and can be applied to several cases of industrial plants e.g. nuclear power plants, thermal power plants, Waste treatment plants, pharmaceutical plants, etc. However, based on experience and research in this area, some areas are identified, which can be improved in the future. For instance, a fuzzy-based modeling approach may be employed to improve the applicability and usefulness of research, risk priority number-based method for maintenance policy selection can be correlated to comparative cost basis maintenance.

The proposed work is based on the bounds constrain program in Genetic Algorithm. However, with different constraints, the same optimization technique can be used. Moreover, additional constraint combinations may be easily introduced to make the optimization problem more realistic. The other parameters of maintenance like the minimum occurrence of particular failures can also be taken into consideration. In this work, four critical pieces of equipment are considered for maintenance optimization; however, the Plate and coil mill plant can be divided into multiple systems and their subsystems for more effective results.

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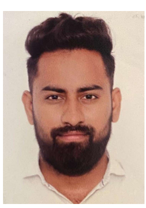

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APPENDIX

Failure Mode Effect analysis of critical components:

Sr no	system/ component	Failure mode	Failure effect	Failure cause	Current practice	chances of failure (C)	Detection (D)	severity (S)	maintainability (M)	RPN =C*D*S*M	Maintenance plan	Suggested remedies
1	Downcoiler	Alignment	The coil does not come out from the Downcoiler and the stripper car not moving forward.	stripper car rack pinion alignment disturbed	rack & pinion alignment adjustment	5	4	3	3	180	Predictive maintenance	To check each part's alignment at regular interval
				stripper car hydro motor bolt loosed	bolt checking and tightening							
			strapping machine shutdown	hose loosed from thread connection	fit the hose with pipe fitting							
		Wear/ breakage	bearing got damaged	high temperature	bearing replacement	3	3	4	3	108	Predictive maintenance	Monitoring of heating parameters
			stripper car guide roll plate welding broken	fatigue load	Plate welding							To check and maintain the load range applied on the plate
		Improper lubrication	strapping machine carriage stuck with rail results in Downcoiler breakdown	The guide wheel jammed due to lack of lubrication	make the guide wheel free and do greasing in it	4	3	4	3	144	Predictive maintenance	change the lubrication oil as per operating parameters conditions

2	Reheating furnace	Damper failure	reheating furnace shut down	position control valve damaged	booster change and oiling in links	3	2	3	3	54	Preventive maintenance	monitoring control valve condition oiling in links at regular intervals
		brakes failure	discharge m/c not coming to the home position	The brake liner was found damaged	brakes change	2	2	3	2	24	Corrective maintenance	optimization of operating parameters
3	Descaler	pressure drop	loss of pressure	leakage in hose	Hose replacement	4	3	2	3	72	Preventive maintenance	maintain the pressure range with a pressure transmitter
		pump tripping	Descaling system abnormal condition coming so Descaler working stopped	The pilot valve not working properly	Pilot valve changed	3	3	3	3	81	Preventive maintenance	Monitoring of pilot valve condition and pressure parameters at regular intervals and keeping stand pilot valve in the spare
4	Steckel mill coiler furnace	pinch roll bending	upper guide plate fall down	Due to heat bottom pinch roll gets bent and foul with the upper guide plate	reassemble done	2	3	4	4	96	Preventive maintenance	proper shear key to be fitted
		pressure drop	The furnace is not lit up	governor problem	governor changed	2	3	3	2	36	Corrective maintenance	To check governors' working conditions with heating parameters at regular intervals