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Reliability Analysis of Polyurethane (PU) Machine

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Abstract

This study evaluated the reliability of an aluminium production line. It utilized the Root Cause Analysis as a maintenance tool to determine the reliability of units of the production line. The maintenance method assigned to a production line depends on the criticality of the root cause of the equipment failure. The root cause, direct cause and instrumental causes of failure were evaluated. Polyurethane production machine was chosen for the analysis. Results showed that equipment/maintenance problems made up the major causes of failure in the production line while management, personnel, procedure error and critical spare parts delays constituted the least. It was also shown in the work that the production line has high availability, reliability and quality. Excel spreadsheet and Matrix Laboratory "MATLAB" programme were used to analyze the results. If a good maintenance approach is adopted; it will decrease equipment failure, decrease production line downtime, better product quality, and an improvement in workers' morale, environmental safety, energy savings and customer satisfaction. The research also guides choosing the best root-cause analysis strategy depending on the requirements of a particular equipment and application.

Keywords: polyurethane machine, production line, reliability, maintenance.

Introduction

According to Keith et al. (2008), reliability is a strategic resource which has single point accountability for providing the long-term business strategy that ensures production capacity, product quality, and best life cycle cost. Reliability measures are necessary for customer requirements compliance. However, measuring reliability does not make a product reliable; only by designing in reliability can a product achieve its reliability targets. The reliability concept is globally applicable in production companies since there is a need to measure the real productive capacity and economic gain of production equipment in planning projections (Stenstron et al, 2016). This research adopted some reliability tools which include statistical probability using Microsoft Excel spreadsheet and MATLAB to analyze and evaluate the failure data.

Aluminium Sheets Production Company in Kaduna has been producing below maximum capacity as a result of failure problems of the turbo-chargers used for the oven. This has affected the reliability, quality and availability of the system and subsequently the targeted aluminium production. For the failure problems to be reduced, there arouse a need for good review of the equipment failure rate, cause of failure, and subsequently proffer the best way and technique to reduce these failures. The aim of this research is to analyze the reliability of individual section of Polyurethane (PU) Machine.

Production Line

The application of traditional reliability theory is severely limited by the complexity of a production line, which is a complex system of mechanical, electrical, and liquid coupling with numerous components, complex structures, and multi-states. Failure modes are also varied, dependent, and uncertain. As a result of the above, (Xue 2009 and Liu 2014) investigated the fault tree method's application from two-state systems to multi-state systems. These techniques extend the scope of conventional reliability analysis techniques, but they do not address the underlying issues.

Literature Review

Today's technological equipment in manufacturing industries is faced with a high level of complexity. Complex machines are required in a competitive business environment. Critical machine reliability improves the production capacity and throughput time in manufacturing cells (Djassemi et al, 2019). Sheng (2018) adopted the Bayesian Network (BN) by exploiting the advantage of uncertainty reasoning and the multi-state expression of BN in a production line to check its reliability, and the systems' faults were identified by calculating the system reliability on the foundation of multi-state probabilities of item. The maximum output of production items could be possible by ensuring minimum shutdown and breakdowns to ensure a reduction of the unavailability and an increase in the reliability of the machines.

Deka et al. (2018), in their investigation on the breakdown and reliability analysis in a process industry, deduced that modern machine failures are mainly caused by their complex nature which could lead to low output. Pareto analysis, RCA and Weibull reliability measures were used in their findings. Wen and Kang (2016), presented a survey of production equipment reliability, based their results on probability models. Bansal and Tyagi (2018), in their investigation on the reliability analysis of screw manufacturing plants, submitted that production systems constitute subsystems operating in series in which failure hardly occurs simultaneously.

According to Uzoigwe (2024), he Reliability-Centered Maintenance programme was implemented to assess its efficacy in food and beverage manufacturing equipment; the study shows the program's revolutionary effects, which include notable decreases in downtime, enhanced asset dependability, and significant cost savings.

Root Cause Analysis

Root cause analysis's primary objective is to identify and record the causes of events so that suitable remedial actions can be implemented to prevent them from happening again and protect workers, the environment, and everyone's health and safety. (Hamali et al., 2023) used the Pareto diagram, Five-Whys Analysis, Root Cause Analysis (RCA) supported by Fault Tree Analysis (FTA), Weibull distribution, and corrective and preventative action to investigate the elimination of breakdown in machinery.

Methodology

The reliability concept is globally applicable in production companies since there is a need to measure the real productive capacity and economic gain of production equipment in planning projections (Stenstron et al, 2016). This research adopted some reliability tools which include statistical probability using Microsoft Excel spreadsheet and MATLAB to analyze and evaluate the failure data. This research made use of theoretical and analytical technique in analyzing the causes of failure and failure rate which were not adopted in the literature review. The research work adopts the guidelines granted by the U.S. Department of Energy (DOE Order NE-STD-1004-92), happening and processing, also reporting production data for failure analysis. The techniques adopted are desk and survey research. The survey technique includes the study of an aluminium production line in Queensway Aluminium Company Limited Kaduna, and a review of relevant documents; necessary dates and time associated to failure were carefully examined. Relevant documents reviewed were:

i. Operating log/company corrective maintenance log books.
ii. Inspection records.
iii. Maintenance records.
iv. Technical meetings minutes.
v. Company annual report sheets.
vi. Procedure and instructions.
vii. Work orders.
viii. Manufacturer data sheet.

The desk work involves referencing technical papers, engineering journals and text relevant to this study. The text includes; Engineering design Handbooks and Reliability, Handbooks on maintenance, operations and maintenance manuals on Equipment Production Lines. Root cause analysis guidance documents, etc. analysis and calculations were focused on Queensway Aluminium Company Limited data collected. The research and desk survey were matched together to yield a final illustration of the causes of equipment failure and the aluminium production line failure rate.

The Polyurethane (PU) Machine

The Polyurethane (PU) machine is the most commonly/widely used sandwich panel production line, established in 1992 in China. It has an average speed of 7m/minute, 410m/hour, and 3300m/day using the ergonomically industrial approach of 8 hours. The machine uses a total power of about 200KW. The PU injection machine has two or four components, from Italy with a double belt laminated conveyor length of 24m. The equipment maintains a high temperature of seventy degree centigrade (70^0C). It has a line dimension of $(L \times W \times H)$ $which\ is$ $86000 \times 7000 \times 3800)mm$. The polyurethane machine produces sandwich panels with a width of sixty to seventy centimeter (60 to 70) cm in thicknesses from 20 to 110 mm. The panels are perforated with a flexible facing, glass fibre, bitum paper, aluminium foil paper, which are fed into the continuous foaming line. The polyurethane density ranges from 35 to 50 kg/m^3. Figure 1 shows the production operation system

Polyurethane (PU) Machine Production Process

Figure 1 shows the polyurethane machine production process.

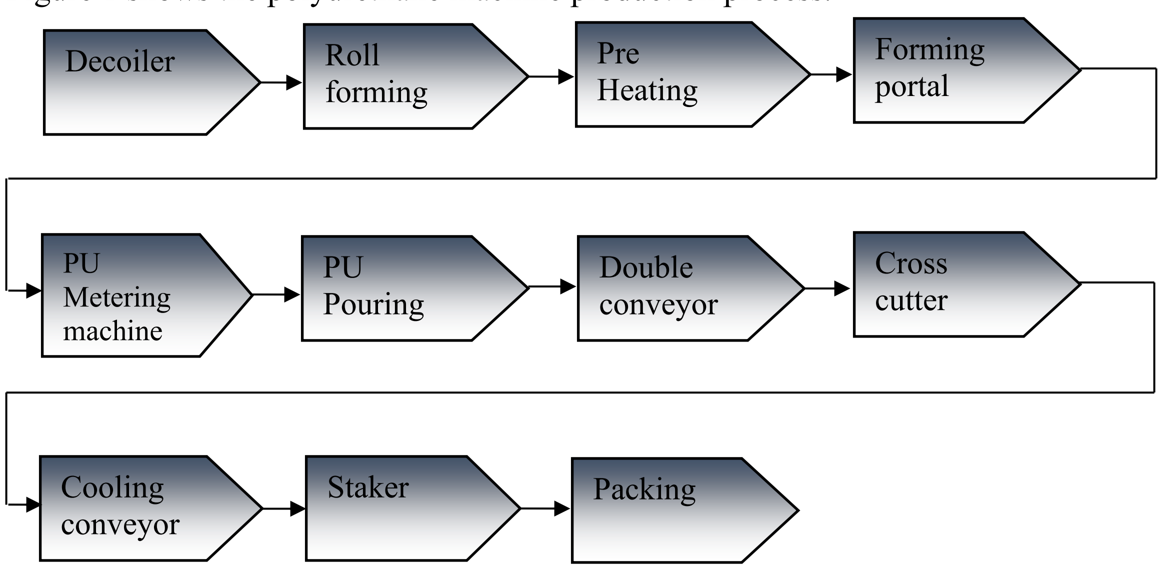

Fig. 1: PU Sandwish Panel Production Line (Source: Survey).

The major causes of failure of the Polyurethane (PU) machine were identified as follows:

i. Lube oil pump electric motor bearing failure.
ii. Gear box shutdown.
iii. Unavailability of manufacturer/vendor.
iv. Failure of electric motor.
v. HP compressor seal gas detector.
vi. Compressor recycle valve malfunction.
vii. Delay of spare parts/materials.
viii. Pneumatic pump failure.
ix. Inadequate follow-up on vibration analysis.
x. Power panel system malfunction (telemecanique contactor, overload and flush socket, relay, inverter, circuit breaker).
xi. Critical Spare Parts could not be identified by the Trade/Crafts.

Root Cause Failure Analysis

The methodologies, guidelines, instructions and worksheet in this work shall be tailored to the guidelines used by the United States Department of Energy (DOE order NE-STD-1004-92); occurrence, reporting and processing of operators data for failure analysis machinery enterprises. The classifier was deduced from the machinery company's documents. The evaluation stage involves the analysis of the data for analyzing the causal factors, summarizing the findings, and grouping accordingly. The causal factor codes and worksheet were used in analyzing the Polyurethane (PU) sandwich panel production line's major failure causes. Tables 1 to 11 is for the analysis.

Seven major failure groups are adopted from the classifier document:

i. Equipment Problem.
ii. Procedure Problem.
iii. Personnel Error.
iv. Design Problem.
v. Training Deficiency.
vi. Management Problem.
vii. Supplier/subcontractor problem.

The above seven groups are enough to analyze any failure. All failure groups constitute of different failure causes.

Table 1: Lube Oil Pump Electric Motor Bearing Failure.

Equipment Problem Subgroup	I	II	III	IV
1A - Defective or failed part		D		
1B - Defective or failed component				
1C – Software failure				
1D – Equipment failure				
1E – Bad equipment job				
1F – Contamination				R

Rate unit subgroup cause
D – Direct Cause.
I – Instrumental Cause.
R – Root Cause.

Description
Direct Cause: IA – Defective or failed component

i. Excessive wear of the bearing lining due to improper lubrication.
ii. Bearing became loose and noisy in its housing.

Instrumental Cause

i. Large charges of electricity.
ii. Misalignment.
iii. Poor bearing mounting during installation.

Root Cause: 1F – Contamination

i. Improper lubrication and contamination of lubrication oil.

Recommended Corrective Actions

i. Review lubricant type, quality and quantity and lubrication method.
ii. Replacement of the failed bearing with the right specification.

Table 2: Gear Box Shutdown.

Equipment Problem Sub-group	I	II	III	IV
1A - Defective or failed component				
1B - Defective or failed material				
1C – Software failure				
1D – Equipment failure		R		
1E – Bad equipment job				
1F – Contamination				I

Rate unit sub-group cause

D – Direct Cause.

I – Instrumental Cause.

R – Root Cause.

Cause Description

1D - Equipment failure.

The vibration sensor might not have been installed properly and was covered with oil particulates and debris.

Recommended Correction Actions

i. The vibration sensor should be installed properly by the service provider.
ii. Predictive and preventive maintenance approach should be carried out periodically on the vibration sensor.

Table 3: Unavailability of Manufacturer/Vendor Management Problem

Management Problem Sub-groups	I	II	III	IV
6A – Inadequate administrative control			I	
6B – Work organization/planning deficiency	R			
6C – Inadequate equipment/operators supervision				
6D – Improper resource allocation				
6E – Policy not adequately defined				
6F – Other management problem			D	

Rate each sub-group cause.

D – Direct Cause.
I – Instrumental Cause.
R – Root Cause.

Cause Description

5B – Improper organizational work policy/planning

i. There was procrastination in the issuance of visa to manufacturer/vendor.
ii. General fear of insecurity of the manufacturer/vendor found in the South-South geopolitical region of Nigerian.

Recommended Corrective Actions

i. Operators should be trained properly.

Table 4: Failure of Electric Motor.

Equipment Problem Sub-groups	I	II	III	IV
1A –Defective or failed component				D
1B - Defective or failed material		R		
1C – Software failure				
1D – Equipment failure				
1E – Bad equipment work				
1F – Contamination				I

What is the reason equipment/material problem a cause?

Rate each sub-group cause
D – Direct Cause.
I – Instrumental Cause.
R – Root Cause.

Cause Descriptions

1A –Defective or failed part

i. Low resistance of the motor which is caused by the degradation of the insulation of the windings due to certain factors such as; overheating, corrosion or physical damage.
ii. Contamination: contamination from dirt, dust and chemical could also be a cause of electric motor failure.
iii. Vibration: vibration could results to many challenges which could cause the electric motor to fail prematurely.

Recommended Corrective Actions

i. The insulation should be checked periodically for signs of wear and replaced to avoid failure due to low resistance.
ii. Electric motors should be away from grinding machines when laying out the workpspace to avoid contaminations.
iii. Electric motors should be checked periodically for vibration using appropriate motor analyzing tool.

Table 5: HP Compressor Seal Gas Detector

Equipment Problem Sub-groups	I	II	III	IV
1A – Defective or failed component				D
1B - Defective or failed material		R		
1C – Software failure				
1D – Equipment failure				
1E – Bad equipment work				
1F – Contamination				I

Rate each sub-group cause

D – Direct Cause.

I – Instrumental Cause.

R – Root Cause.

Cause Descriptions

1A –Defective or failed part

Seal gas system found highly contaminated with water- like liquid.

Recommended Corrective Actions

Failure of this kind could be prevented by having a good partnership with manufacturer/vendor that can provide active solution.

Table 6: Compressor Recycle Valve Malfunction

Equipment Problem Sub-groups	I	II	III	IV
1A – Defective or failed component			D	
1B - Defective or failed material		R		
1C – Software failure				
1D – Equipment failure				
1E – Bad equipment work				
1F – Contamination			R	

What is the reason equipment/material problem a cause?

Rate each sub-group cause

D – Direct Cause.

I – Instrumental Cause.

R – Root Cause.

Cause Descriptions

i. Instrument or electrical problem.
ii. Instrument air failure to the valve to close which result to tripped of the PU sandwich panel machine compressor.

Recommended Corrective Actions

i. Preventive maintenance technique to be adopted for this component.
ii. Machine air regulators, positioners and controllers should be routinely checked for proper functionality.

Table 7: Delay of Spare Parts/Materials

Management Problem Sub-groups	I	II	III	IV
6A – Inadequate administrative control			I	
6B – Work organization/planning deficiency	D			
6C – Inadequate equipment/operators supervision				
6D – Improper resource allocation				
6E – Policy not adequately defined				
6F – Other management problem		R		

Rate each sub-group cause
D – Direct Cause.
I – Instrumental Cause.
R – Root Cause.

Cause Description

6F – Other management problem

i. Management to act proactively with the agency in charge of tariff and trade of imported spare parts/materials.

Recommended Corrective Actions

i. Management should be properly informed on government regulations about imported spare parts so as to negotiate for waivers.
ii. Management should improve in stock inventory so as to avoid unnecessary delays of critical spare parts.

Table 8: Pneumatic Pump Failure

Equipment Problem Sub-groups	I	II	III	IV
1A – Defective or failed component			D	
1B - Defective or failed material			I	
1C – Software failure				
1D – Equipment failure				
1E – Bad equipment work				
1F – Contamination			R	

Rate each sub-group cause
D – Direct Cause.
I – Instrumental Cause.
R – Root Cause.

Cause Descriptions

1A –Defective or failed part

i. Poor machine design, using low-quality fluids and low contamination control.
ii. Air found in the hydraulic fluid when subjected to pressure by the pneumatic pump.

Recommended Corrective Actions

i. Replace the pneumatic pump with the correct specification.
ii. Good quality hydraulic fluid should be used with correct specification to avoid contamination.

Table 9: Inadequate Follow Up on Vibration Analysis.

Training Deficiency Sub-groups	I	II	III	IV
5A –No training provided	R			
5B – Insufficient practice or hands on experience				D
5C – Inadequate content				
5D – Insufficient refresher training		I		
5E – Inadequate presentation or material				

Rate each sub-group cause

D – Direct Cause.
I – Instrumental Cause.
R – Root Cause.

Cause Description
6A – No training provided
  i. Inadequate training for the personnel that handles vibration analysis.

Recommended Corrective Action
  i. Training programmes be design and put in place for the vibration analysis personnel.
  ii. Vibration analysis reports to be sent to the maintenance personnel for proper implementation.

Table 10: Power Panel System Malfunction

Equipment Problem Sub-groups	I	II	III	IV
1A – Defective or failed component				D
1B - Defective or failed material				
1C – Software failure				
1D – Equipment failure		R		
1E – Bad equipment work				
1F – Contamination				I

Rate each sub-group cause
D – Direct Cause.
I – Instrumental Cause.
R – Root Cause.

Cause Descriptions
1B - Defective or failed material

i. The circuit breaker is being overloaded, high electrical voltage, damage relay and inverter.

Recommended Corrective Actions

i. Appropriate components should be chosen for the task.
ii. The following damaged components; telemecanique overload relay contactor, flush socket be replaced.

Table 11: Critical Spare Parts could not be identified by the Trade/Crafts.

Personnel Error Problem Sub-groups	I	II	III	IV
3A –Inadequate work environment		D		
3B – Inattention to detail				
3C – violation of requirement or procedure	R			
3D – verbal communication problem				

Rate each sub-group cause
D – Direct Cause.
I – Instrumental Cause.
R – Root Cause.

Cause Descriptions
3C – violation of procedure

i. The partition used as store was not properly arranged, the materials were scattered, hence, not easy for the store keeper to identify critical spare parts.
ii. Loss of spare parts identification tags and manufacturing spare parts number.

Recommended Corrective Action

i. Replace worn out parts of the pump and ensure pump is operated according to manufacturer/vendor specifications.

Data Presentation

The data gathered from the following; operating log/company corrective maintenance log books, inspection records and maintenance records of the polyurethane (PU) panel production line are presented in Tables 12 to 17 in Appendix A. The tables contain the frequency of failures per machine, start time, stop time, hours run per day. The mean time to repair (MTTR) is the average time taken to repair the machine, from when the equipment fails to the period it is operational again. The mean time before failures (MTBF) is the numbers of time the equipment fails under survey.

Results

Results of data gathered and evaluated from the Polyurethane Sandwich Panel Production Line and the Metcoppo Tiles Production Machine are discussed.

Polyurethane (PU) Sandwich Panel Production Line (MC1)

The findings of the least and major causes of the Polyurethane (PU) Production Line failure revealed the necessity of designing a database for the Queensways Aluminium Company production line failure modes and failure rate by adopting existing survey data. For machine reliability analysis, what is required from the model adopted in this study includes; expected frequency of failures, mean time before failures (MTBF), mean time to repair (MTTR), reliability and availability parameters. By adopting the root cause analysis model, several reliability characteristics of the aluminium sheet production line were presented.

Table 18: Worksheet Summary.

S/No	Problem/Deficiency Group	No. of Occurrence	Expressed in %
i.	Equipment/material	7	63.6
ii.	Procedure problem	Nil	Nil
iii.	Personnel error	1	9.09
iv.	Design problem	Nil	Nil
v.	Training deficiency	1	9.09
vi.	Management problem	2	18.18
vii.	Supplier / subcontractor problem	Nil	Nil

Table 18 shows clearly that equipment/material failure contains the major causes of failure with a percentage of 63.6%. Other causes of component/equipment/ material failures like instrumentation and calibration related with the production line safety protection system which include pneumatic control, pressure control, anti-surge protection and vibration monitoring. Using the findings of the complex instrumentation, automation and state-of-the art machine/equipment/component assembled on the platform and the inadequate training and exposure to local manpower, inadequate training was seen as direct failure causes.

Training deficiency and personnel error constituted 18.18% of the cause of failure in the production line. Management problem alone constitute 18.18% of the overall causes of failure found in the equipment, because of job organization/planning deficiency and poor administrative control. The current PU machine production capacity is 7m/min, 410m/hr and 3300m/day.

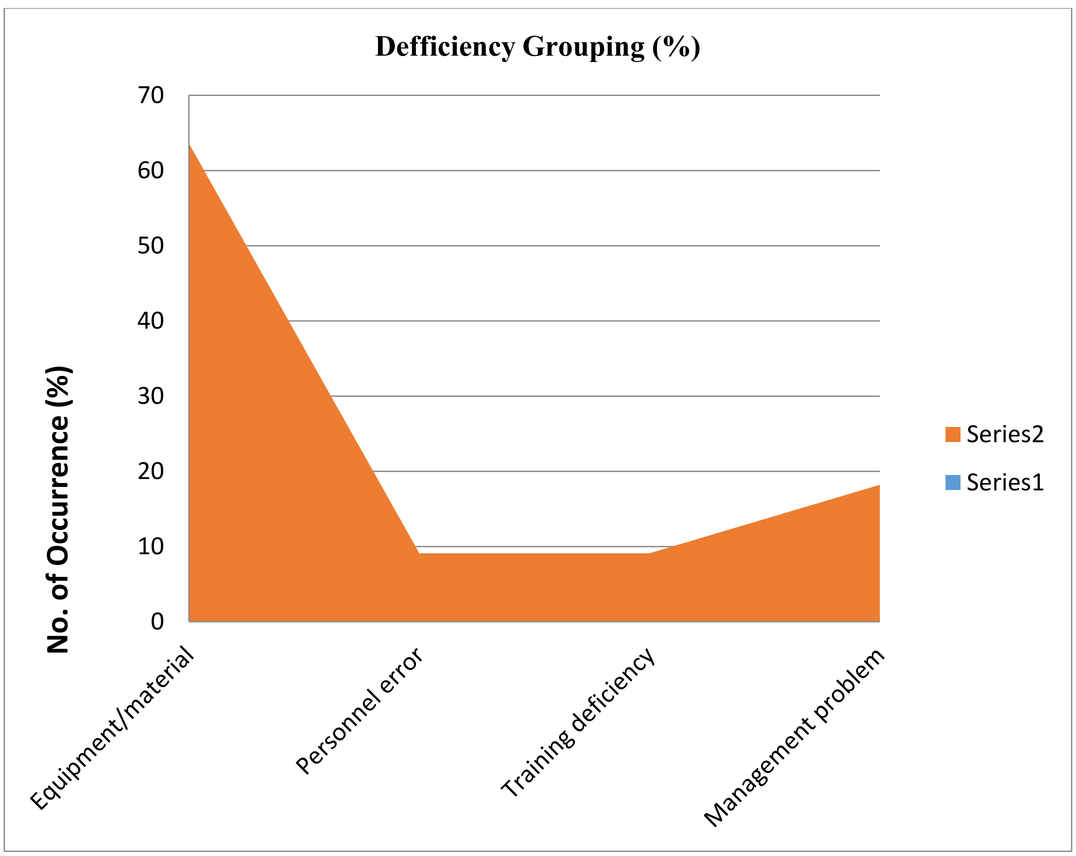

Figure. 2: Response surface plot for deficiency grouping of PU machine line From the month of February to July 2024.

Figure 2 reveals the response surface plot for deficiency grouping of PU machine line for February to July 2024. The figure reveals that training deficiency seen amongst the operators as the least cause of failure in the production line. The personnel error which results to the machine downtime is traceable to inadequate training and inattention to details.

Table 19: Equipment Key Performance (EP).

			PARAMETERS			
S/NO/ MONTHS	**MCQ (%)**	**MTBF (HRS)**	**FAILURE RATE λ (%)**	**MTTR (HRS)**	**AVAIL-ABILITY(%)**	**RELIA-BILITY(%)**
1. Feb	99	15.92	6.3	4.08	80	77
2. March	99	25. 13	3.9	5.54	82	81
3. April	99	51.32	1.95	2.02	96	96
4. May	99	33.7	2.9	10.3	77	74
5. June	99	30.67	3.3	4.53	87	86
6. July	99	27.69	3.6	5.91	82	81

Table 19 indicates that the equipment availability that is a sign of the general function of the polyurethane machine is 80% for February and 82% for the month of July respectively. The machine availability is highest at 96% for the month of April, while the lowest was recorded for May (77%). The value for May was lowest due to the Polyurethane machine schedule maintenance. The average plant availability is 84%. The machine reliability showed 77% for the month of February, 81% for the month of July. The machine reliability is highest at 96% for the month of April while the lowest was recorded for the month of May as also shown in the machine's availability. The machine reliability results shows that machine reliability could also lead to its availability.

MATLAB PLOTS FOR PU SHEET PRODUCTION LINE

Availability of PU machine vs. months of the year

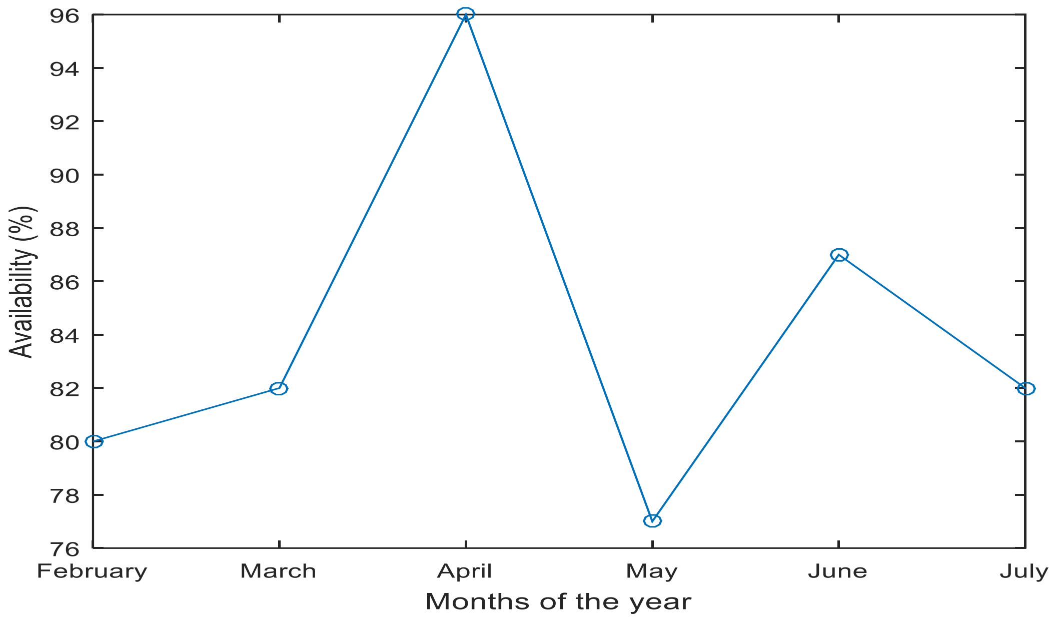

Figure 3: Availability of PU machine for months of February to July 2024. 2017

Figure 3 shows the MatLab plot of the PU production line against the months of the year. It is revealed in the figure that the machine's availability was at its peak in April and least in the month of May.

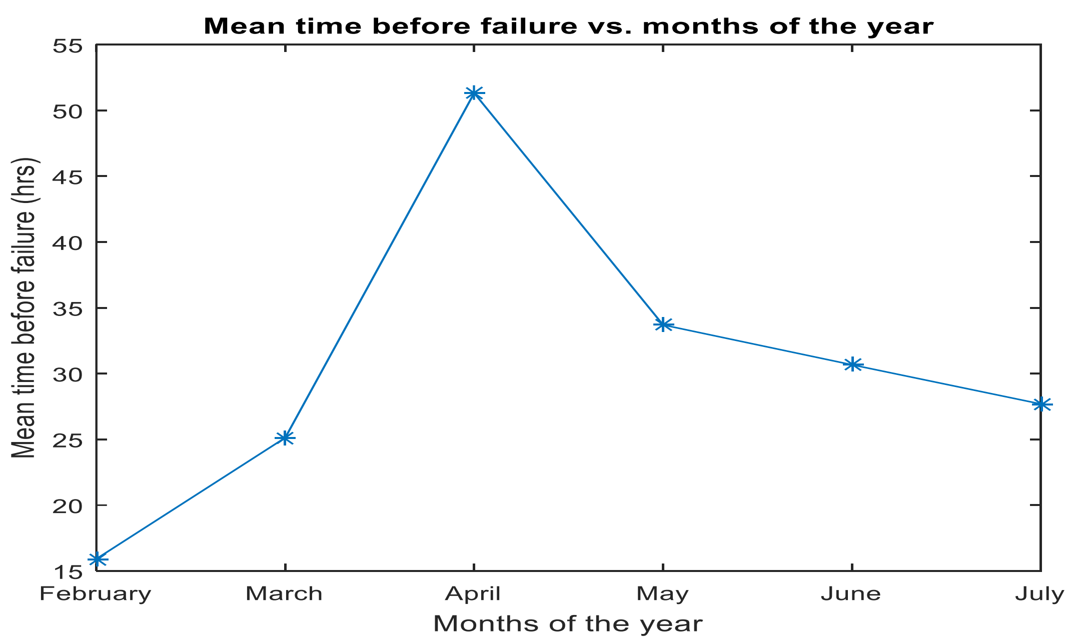

Figure 4: MTBF of PU machine for months of February to July 2024.

Figure 4 shows that the highest MTBF was attained in April (51.32hrs). This is obtainable because of downtime reduction, maintenance activities and failures for the month of April, while that of February was the least. The MTBF average 30.74 hours for the period covering February to July which is six months. The Mean Time to Repair (MTTR) in figure 4.4 clearly reveals two larger figures of 5.91hrs for July and 10.3hrs for the month of May. The lowest MTTR was attain in the month of April (2.02) and at its peak in the month of May (10.3hrs).

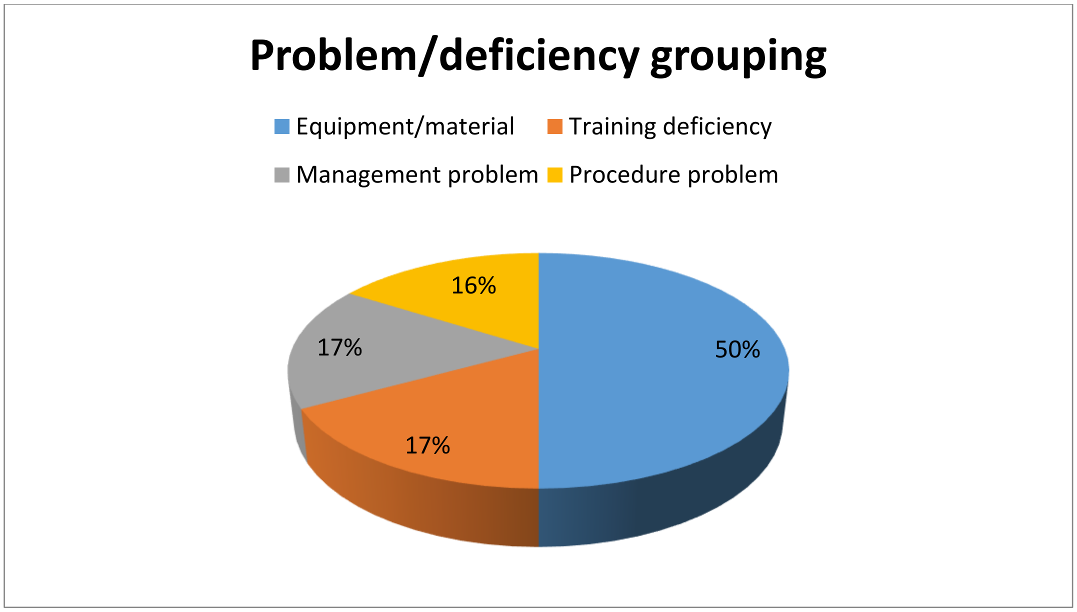

Figure 5: Deficiency grouping of PU production line for July to October 2024.

Figure 5 is a pie chart displaying the percentage of the problem/deficiency grouping. The research shows that equipment/material deficiency was highest 50%, training and management problem 17% each due to inadequate administration, technical knowhow and unplanned downtime while procedure problem was seen as the least with 16%.

Discussion of Results

Key Performance Indicators (KPI) of MC1

Table 4.2 reveals that the key performance indicators (KPI) for February are 15.92hrs, while that of July is 27.69hrs. The highest MTBF was attained in the month of April (51.32hrs). The later is possible as a result of downtime reduction, maintenance activities and failures for the month of April, while that of February was seen as the least.

The failure rate for the month of July is also 3.6%. The lowest was in April which is 1.95% while the highest was attained in February which is 6.3%. The failure rate average is 3.7% for the period covering February to July that is six months. The results for the machine MTBF, MTTR, failure rate, availability and reliability are comparable and agreeable with expert suggestion and also published production performance reports and evaluation. (See Table 4.2 and Figure 4.5).

Mean time to repair vs. months of the year

The Mean Time to Repair (MTTR) in Figure 4.5 clearly reveals two larger figures of 5.91hrs for the month of July and 10.3hrs for the month of May. The lowest MTTR was in the month of April (2.02) and the highest was for the month of May (10.3hrs).

Table 4.1 clearly reveals that component/material failure constitutes 62.8%, training deficiency, management problem and personnel error represents 15% while external factors represent 5.7%. Components/material constitutes a major cause of failure of the Aluminium production line. Machine contamination, lubrication oil and other components like gear box failure, bearing, and control panel of the production line were critical causes of the Aluminium sheet production line.

Conclusion

From the study and results found, the following conclusions were obtained:

a. The quality, reliability and availability of a machine/component and processes may be improved through detecting and removing the causes of failures at early stages.
b. Equipment/material failure constitutes a major cause of failure of the aluminium sheet production line which is 63.6%. Training deficiency and personnel error represents 9.09%, while management problem is 18.18%.
c. To minimize failures obtain greater production capabilities, machine reliability and availability, the company must shift away from traditional method which the company adopted breakdown maintenance to proactive

maintenance and management philosophies (preventive, predictive and corrective) maintenance approach.

Recommendations

From the investigation and findings obtained, it is therefore recommended that:

a. Machine operators should be trained by experts on the use of industrial machines that will benefits the company by boosting its staffing level at minimal cost.
b. The company should adopt proactive maintenance philosophies such as Reliability-Center Maintenance (RCM).

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APPENDICES

APPENDIX A: TOTAL OPERATING HOURS FOR POLYURETHANE MACHINE

Table 12: Total Operating Hours for the Month of February, 2024.

Date	Start Time	Stop Time	Easy Starts	Hours Run Per Day	Failure
01/2/24	9:00	2:00	1	5.00	0
02/2/24	8:00	3:00	1	5.00	0
03/2/24	9:05	1:55	1	6.55	0
04/2/24			0	0.00	0

05/2/24	0:00	0:00	0	0.00	0
06/2/24	8:25	11:00	1	6.35	1
07/2/24	8:45	11:50	2	6.05	1
08/2/24	8:00			8.00	0
09/2/24	8:59		2	6.01	1
10/2/24	10:00	2:25	0	5.35	0
11/2/24				0.00	
12/2/24	0:00			0.00	
13/2/24	9:20		0	6.40	1
14/2/24	11:00		1	5.00	1
15/2/24	9:35		0	5.25	0
16/2/24	8:00		0	8.00	0
17/2/24	10:00	12:00	1	4.25	1
18/2/24	0:00			0.00	
19/2/24				0.00	
20/2/24	11:30		1	4.30	0
21/2/24	8:30		0	7.30	1
22/2/24	8:00		0	8.00	0
23/2/24	8:00		0	8.00	0
24/2/24	9:05	2:30	1	5.55	1
25/2/24				0.00	
26/2/24				0.00	
27/2/24	9:00	12:00	0	7.00	0
28/2/24	8:00		1	8.00	0
Total			**13**	**127.36**	**8**

Source: Queensway Aluminium Company Operations Log Book.

Table 13: Total Operating Hours for the Month of March, 2024.

Date	**Start Time**	**Stop Time**	**Easy Starts**	**Hours Run Per Day**	**Failure**
01/3/24	8:00	12:00	1	8.00	0
02/3/24	8:00	3:00	1	7.00	0
03/3/24			1		0
04/3/24	10:10		0	5.50	0
05/3/24	8:00		0	8.00	0
06/3/24	8:00		1	8.00	0
07/3/24	8:45	12:00	0	7.15	0
08/3/24	8:00		0	8.00	0
09/3/24	9:50		1	6.10	0
10/3/24			0		0
11/3/24	10:00	2:25		5:35	
12/3/24	0			0.00	
13/3/24	11:20		0	4.40	1
14/3/24	11:00		1	5.00	1
15/3/24	9:00		0	7.00	0
16/3/24	8:00		0	8.00	0
17/3/24	10:00	12:00	1	4.25	1
18/3/24				0.00	
19/3/24	9:42	3.00		5.48	1
20/3/24	11:30		1	4.30	1
21/3/24	8:00		0	8.00	0
22/3/24	8:00		0	8.00	0
23/3/24	8:00		0	8.00	0

24/3/24				0	
25/3/24	8:50	12:00	1	7.10	0
26/3/24	9:45	2:30	1	4.15	
27/3/24	10:00	2:00	0	5.00	1
28/3/24	8:00		1	8.00	0
29/3/24	9:00		0	7.00	0
30/3/24					
31/3/24					
Total			**11**	**150.78**	**6**

Source: Queensway Aluminium Company Operations Log Book.

Table 14: Total Operating Hours for the Month of April, 2024.

Date	Start Time	Stop Time	Easy Starts	Hours Run Per Day	Failure
01/4/24					
02/4/24	8:00			8.00	
03/4/24	10:10		1	8.50	0
04/4/24	8:00		0	8.00	0
05/4/24	9:00		0	7.00	0
06/4/24	8:00		1	8.00	0
07/4/24					
08/4/24	10:00	2:25	0	7.00	
09/4/24	9:50			8.00	
10/4/24					
11/4/24					
12/4/24	8:00			8.00	0
13/4/24	11:20		0	7.40	1
14/4/24					
15/4/24	8:20			6.40	
16/4/24			0		0
17/4/24	9:00			7.00	
18/4/24	8:10			7.50	
19/4/24	8:25			7.35	
20/4/24	10:30		1	5.30	1
21/4/24					
22/4/24	8:00			8.00	
23/4/24					
24/4/24	8:45			7. 15	
25/4/24		12:00		8.00	
26/4/24		12:00		8.00	
27/4/24	10:00		0	6.00	1
28/4/24					
29/4/24					
30/4/24	8:00			8.00	
Total			**6**	**153.95**	**3**

Source: Queensway Aluminium Company Operations Log Book.

Table 15: Total Operating Hours for the Month of May, 2024.

Date	Start Time	Stop Time	Easy Starts	Hours Run Per Day	Failure
01/5/24					
02/5/24	8:00	12:00		8.00	
03/5/24	9:10			6.50	
04/5/24	8:30			7.30	
05/5/24	8:40			7.20	
06/5/24					
07/5/24					
08/5/24	8:00		0	8.00	
09/5/24	9:50		1	6.10	
10/5/24	10:00	15:25		5.35	1
11/5/24	9:00			7.00	
12/5/24	8:20			7.40	
13/5/24					1
14/5/24					
15/5/24	9:00			7.00	
16/5/24	8:00		1	8.00	
17/5/24	10:00	12:00	1	4.25	1
18/5/24	10:20			5.40	
19/5/24	11:00			5.00	
20/5/24					
21/5/24					
22/5/24	8:00			8.00	
23/5/24	8:00			8.00	
24/5/24	9:40	14:00	1	5.20	1
25/5/24	11:30			0.00	
26/5/24	8:00			0.00	
27/5/24					
28/5/24					
29/5/24	9:00		0	7.00	
30/5/24	8:50	12:00	1	7.10	
31/5/24	9:00			7.00	
Total			**5**	**134.8**	**4**

Source: Queensway Aluminium Company Operations Log Book.

Table 16: Total Operating Hours for the Month of June, 2024.

Date	Start Time	Stop Time	Easy Starts	Hours Run Per Day	Failure
01/6/24	8:20			6.00	
02/6/24					
03/6/24	9:00			7.00	
04/6/24					
05/6/24	8:40			7.20	
06/6/24	9:00			7.00	
07/6/24	8:00			8.00	
08/6/24	8:52		0	7.08	
09/6/24					
10/6/24	8:00	14:20		7.20	
11/6/24	9:55		1	6.05	

12/6/24					
13/6/24	10:00	12:00		6.00	1
14/6/24	9:45			6.15	
15/6/24	9:00	15:30		6.30	1
16/6/24					
17/6/24					
18/6/24	8:00		1	8.00	
19/6/24	11: 10			4.50	1
20/6/24	10:48	13:50		5.02	1
21/6/24	10:20			5.40	
22/6/24	8:00			8.00	
23/6/24					
24/6/24	8:00			8.00	
25/6/24	8:00	12:00	1	8.00	
26/6/24	8:00	14:30		6.00	
27/6/24	9:40			5.20	
28/6/24	11:35			4.25	1
29/6/24	8:00		0	8.00	
30/6/24					
Total			**3**	**153.35**	**5**

Source: Queensway Aluminium Company Operations Log Book.

Table 17: Total Operating Hours for the Month of July, 2024.

Date	Start Time	Stop Time	Easy Starts	Hours Run Per Day	Failure
01/7/24	8:00		8.		
02/7/24	9:45		6.15	1	
03/7/24	8:00	12:00	8.00		
04/7/24	9:00		7.00		
05/7/24	8:00		8.00		
06/7/24	8:00		8.00		
07/7/24	00				
08/7/24					
09/7/24					
10/7/24	8:52		6.05		
11/7/24	9:55		7.08		
12/7/24	8:00	14:20	7.20		
13/7/24	10:00	12:00	6.00	1	
14/7/24					
15/7/24					
16/7/24					
17/7/24	9:00	15:45	5.45	1	
18/7/24	8:00		8.00		
19/7/24	10: 10		5.50		
20/7/24	10:40	16:00	4.20	1	
21/7/24					
22/7/24					
23/7/24	10:00		6.00		
24/7/24	8:00		8.00		
25/7/24	8:00		8.00		
26/7/24	8:00	13:30	6.00		
27/7/24	9:40		5.20		
28/7/24					
29/7/24					

30/7/24	9:05	12:00	6.55	
31/7/24	9:50	14:55	4.05	1
Total			**138.43**	**5**

Source: Queensway Aluminium Company Operations Log Book.

APPENDIX B ANALYTICAL MODEL FOR POLYURETHANE MACHINE

$$MTBF = \frac{Total\ operating\ hours\ of\ the\ machine}{Total\ number\ of\ failures} \quad (1)$$

$$\lambda = \frac{1}{MTBF} \quad (2)$$

$$MTTR = \frac{Total\ outage\ time}{Total\ number\ of\ failures} \quad (3)$$

$$Machine\ availability = \frac{MTBF}{MTBF + MTTR} \quad (4)$$

Machine reliability $R(t) \ = e^{-\lambda t}$ (5)

$$Machine\ Quality\ (MC\ QTY) = \frac{Good\ sheets\ Produced}{Overall\ Sheets\ Produced} \quad (6)$$

APPENDIX C: MATLAB CODES: FOR MC1

```
y= [15.92,25.13,51.32,33.7,30.67,27.69];
figure, plot(y, '-*')
set(gca,'xtick',1:6,...
'xticklabel',{'February', 'March', 'April', 'May', 'June', 'July'})
xlabel('Months of the year')
ylabel('Mean time before failure (hrs)')
title('Mean time before failure vs. months of the year')
holdon
y1=[4.08,5.54,2.02,10.3,4.53,5.91];
figure, plot(y1, '-d')
set(gca,'xtick',1:6,...
'xticklabel',{'February', 'March', 'April', 'May', 'June', 'July'})
xlabel('Months of the year')
ylabel('MTTR (hrs)')
holdon
y1=[80,82,96,77,87,82];
figure, plot(y1, '-o')
set(gca,'xtick',1:6,...
'xticklabel',{'February', 'March', 'April', 'May', 'June', 'July'})
xlabel('Months of the year')
ylabel('Availability (%)')
holdon
```