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A Reliability-Centered Maintenance Study for an Individual Section-Forming Machine

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Abstract: This study investigated the breakdown trend in an automated production with an aim to recommend the application of reliability-centered maintenance (RCM) for improved productivity via a new preventive maintenance (PM) program. An individual section-forming machine (ISM)—a glass blowing machine for making glass bottles—was used as the case study for an automated production system. The machine parts and the working mechanisms were analysed with a special focus on methods of processes and procedures. This will enable the ISM maintenance department to run more effectively and achieve its essential goal of ensuring effective machine operation and reduction in machine downtime. In this work, information is provided on the steps and procedures to identify critical components of the ISM using failure modes and effect analysis (FMEA) as a tool to come up with an optimal and efficient maintenance program using the reliability data of the equipment's functional components. A relationship between the failure rate of the machine components and the maintenance costs was established such that using the recommended PM program demonstrates evidence of an improvement in the machine's availability, safety, and cost-effectiveness and will result in an increase in the company's profit margin.

Keywords: reliability centered maintenance (RCM); individual section-forming machine; failure analysis; risk analysis

1. Introduction

The high level of competition among industries and businesses has made the survival battle tremendously strong. All over the world, producers are striving to further reduce production time loss as production time has cost implications while customers are more concern about the safety and reliability of the products [1]. This quest also includes employees who desire a safe work environment [2]. In the time past, testing and analysis used to be methods to measure reliability, this is no longer obtainable. The focus is on anticipating the factors that lead to failure and ensure that such factors are prevented from occurring frequently using a robust design [3]. To reach this goal, the decrease in the cost of operation is set as a high priority [4]. The study of reliability and maintainability in any manufacturing outfit plays a crucial role in ensuring the smooth running of the production process because it ensures production continuity as well as product quality [5].

Maintenance has been referred to as a single largest controllable cost which can be used to improve productivity through attempts to improve different maintenance policies [6]. A decision-making tool that has been widely implemented is reliability-centered maintenance (RCM). RCM is a tool usually used to understudy the failure pattern of a system so as to be able to make decision on best strategy that can be deployed to ensure that a system achieves the desired level(s) of operational reliability, safety, and readiness and then environmental safety in the most economical manner [7]. RCM is also a systemic consideration for functions, failures, safety and cost-effectiveness of maintenance practices. It is a process that can point to what should be done to guarantee a machine availability of the machine, performing intended functions efficiently [8]. Over the 30 years of implementing RCM, it has been tested and confirmed to be an effective preventive maintenance (PM) optimization strategy; a method that has enjoyed increasing popularity in a wide range of different industrial setups [9]. PM's objective is usually to crunch the probability of having a non-scheduled maintenance, which typically comes at a high cost. Bolu (2013) established the relationship between the measurement of maintenance performance and productivity as the major determinants for maintenance costs by adopting the following equations:

$$Cost\ of\ Maintenance = \frac{\text{Total Maintenance Cost}}{Total\ Maintenance\ Hour} \quad (1)$$

and

$$Maintenance\ Cost\ Component = \frac{\text{Total Maintenance Cost}}{Production\ Output} \quad (2)$$

therefore

$$Cost\ Reduction\ Ratio = \frac{Routine\ Service\ Workload}{Cost\ of\ Maintenance\ Hour} \quad (3)$$

given

$$Routine\ Service\ Workload = \frac{Planned\ Maintenance\ Hour}{Total\ Maintenance\ Hour} \quad (4)$$

Implying that the overall objective of the maintenance function is to support the production department by keeping facilities in proper running condition at the lowest possible cost [10]. For many other machines, RCM has been a successful PM strategy, and this time, it is being tailored for use in an individual section-forming machine (ISM) to aid the design of a planned component replacement (PCR) schedule [11]. This research aims to examine the present maintenance culture of an ISM in a glass bottle molding industry and to establish an RCM plan on this machine. From this, the PM intervals that give the best performance values were identified for an optimum maintenance plan and reduction in service period and frequency.

1.1. Brief Description of Individual Section-Forming Machine (ISM)

The individual section-forming machine (ISM) is an automatic machine used in producing hollow glass containers having narrow or wide necks. The machine is designed to be extremely flexible, hence, it is very efficient for the production of a very large range of containers depending on the mold installed. A furnace is usually an integral compartment of an ISM. It heats to over 1400 °C to melt the glass. The molten glass passes through a forehearth to the feeder where it is cut into uniform gobs of glass, i.e, the liquid glass drops by a thermal shearing and distribution system as shown in Figure 1. An overview of an ISM in action was shown in Figure 2 with an insert of a formed bottle.

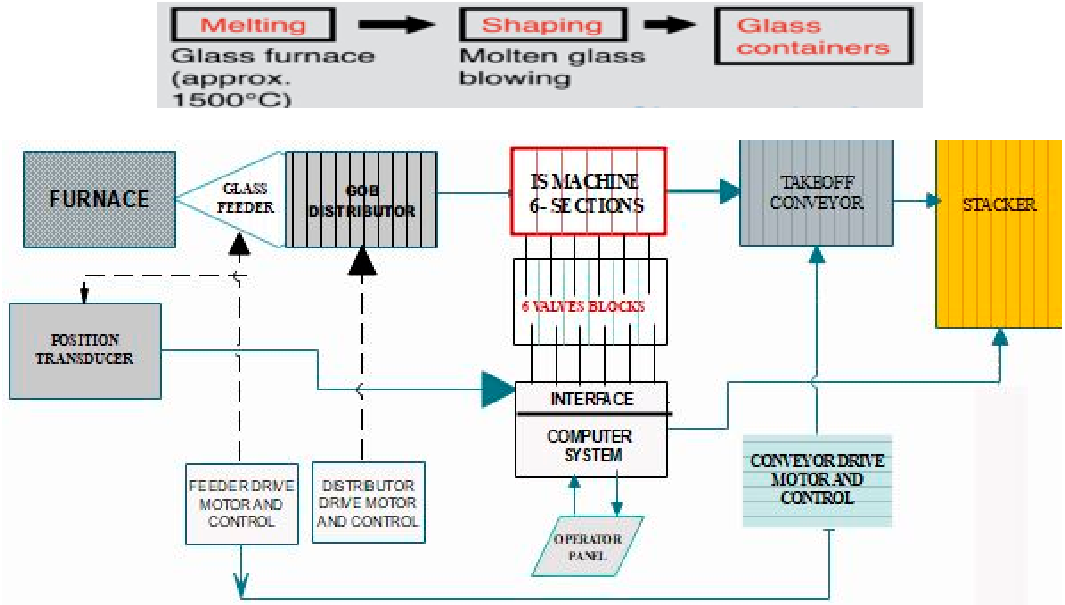

Figure 1. Process flow chart of a typical individual section-forming machine (ISM) [12].

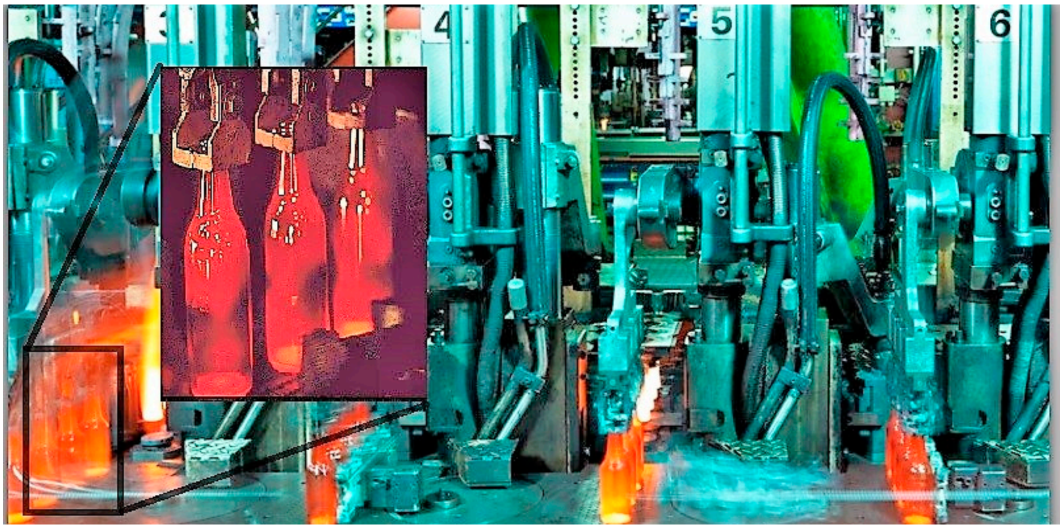

Figure 2. An overview of a typical ISM showing the operation of the plunger mechanism for take-out (Enlarged) [13].

After this, the gobs are sent to an ISM where the temperature reduces to below 1200 °C, and the gobs are injected into the molds. The ISM molds are in two sets—"the blank" and "the blow" [14]. As described in Figure 3 below, the forming section is pneumatically driven, whereas, in the feeder mechanism, the gobs distributor and the pushers can be controlled by servo control or stepping motors. A solenoid–pneumatic valve block controlled by an electronic timer controls the mechanisms in all sections automatically [15].

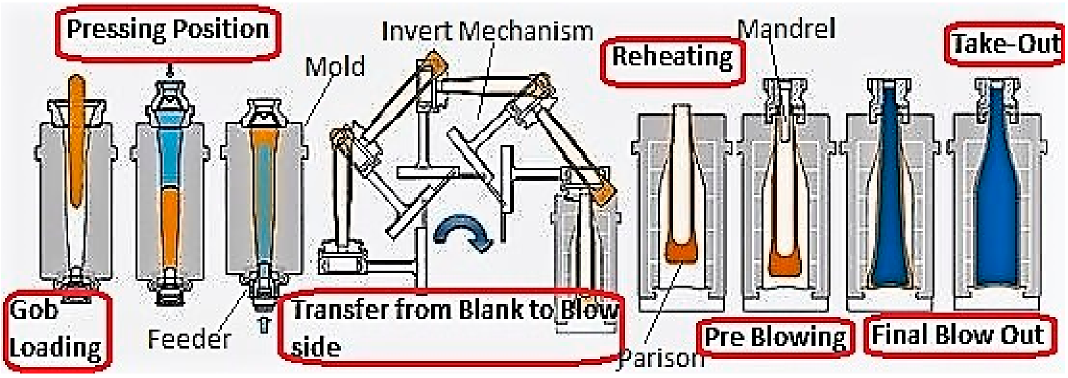

Figure 3. Diagram showing the main operations of an ISM [16].

Owing to the servo-controlled gob distributor, the number of machine sections to be used and the feeding sequence can be programmed to make the process completely automated [12]. The electronic pushers transfer the items from the cooling plate to the conveyor accurately, thus, improving item alignment on the conveyor. The time needed for job changes is, therefore, reduced as the pushers can be completely programmed [13]. As shown in Figure 1, there are six (6) independent sections which can be controlled and operated. Any form of operation or maintenance, such as the replacement of molds, can be performed without affecting other sections. As a matter of fact, different types and shapes of molds can be installed in different sections. The ISM is a critical success factor in glass bottle production, and it is more rewarding if kept at the optimum in-service condition [17].

1.2. Overview and Review of RCM Related Work

Like many other maintenance planning tools, RCM is used to preserve an item's functionality. RCM seeks to curtail the criticality of failure as all failures can never be eradicated [18]. The first priority of RCM is safety. In cases where safety is not jeopardised, the priority becomes maintenance justified by the ability to complete the mission of availability and reliability and then the final priority is based on cost-effectiveness [19]. These cumulating into making use of RCM for the design of the system; system's operation modes; the maintenance methods and practices; logistics, and costs data (analysis) to improve operating capability of such system(s). RCM has been found to be an integration of preventive maintenance (PM), Predictive testing and inspection (PT&I), reactive maintenance (repair) and proactive maintenance to minimize maintenance cost and downtime and consequently increase the probability of function-ability of a machine over its expected lifespan; this is succinctly represented in Figure 4 below while Figure 5 highlighted the flowchart of RCM analysis [20].

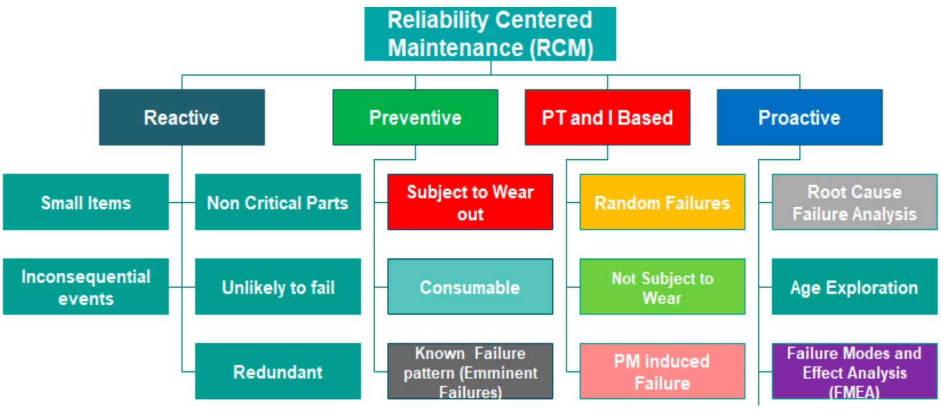

Figure 4. Components of a reliability-centered maintenance (RCM) program.

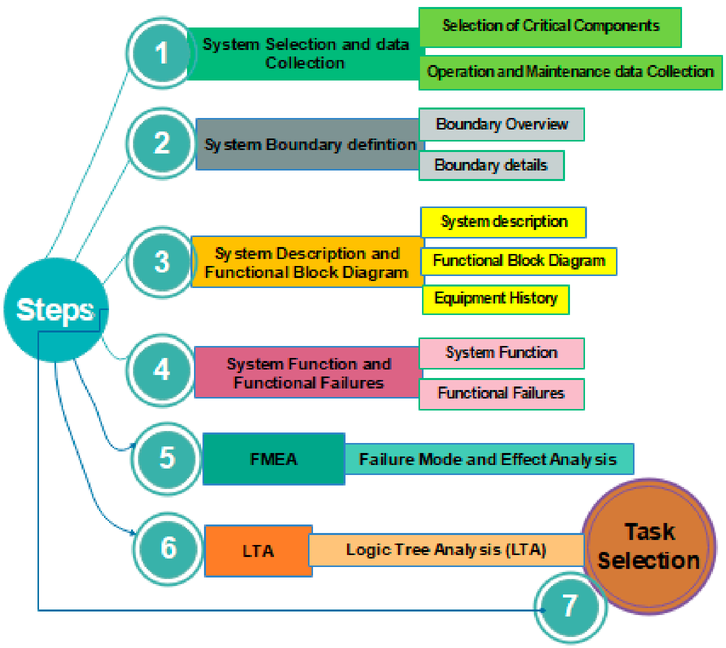

Figure 5. A flowchart for the RCM analysis [21].

RCM should be a continuous process that requires sustaining because it is known that any system's best maintenance can only sustain a system to its inherent reliability and availability level within the operating context [22]. The condition-monitoring system (CMS) is an integral component of RCM to increase productivity and reliability of machines as shown in Figure 6 below (Item 3). The conditions leading to failure mode must have been or be investigated using sensors like accelerometers, encoders, current/torque sensors, and pressure sensors as well as temperature sensors [23].

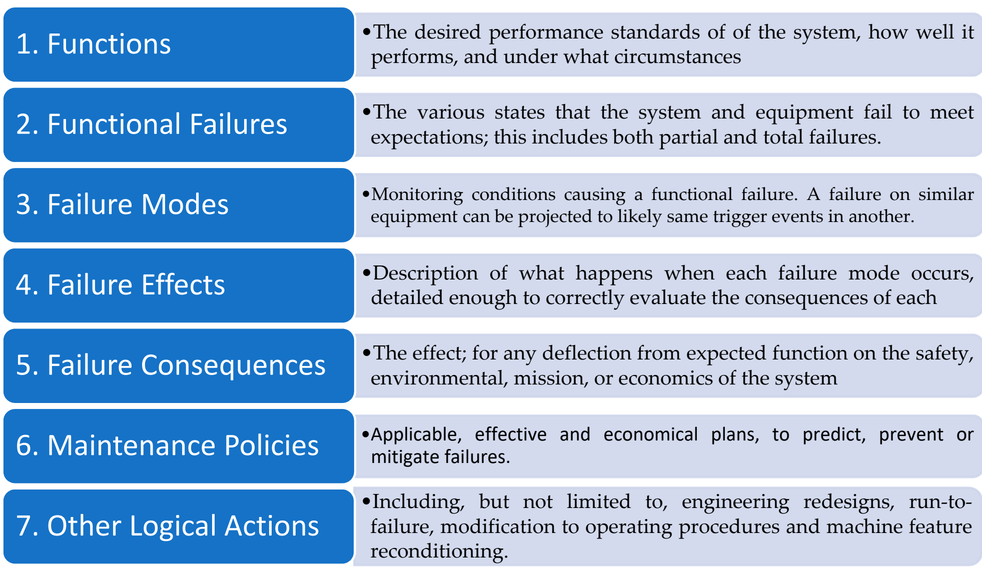

Figure 6. An overview of the items of the RCM process in sequence [24].

From the past researches, it is evident that RCM has been used as a tool to sort out failure problems ranging from the field of medicine to military to building-related technologies to automotive to aviation and, of course, industrial and production to mention few. Wang et al. (2000) [25] carried out an RCM analysis of process equipment using heat exchangers as a case study. Results indicated that RCM could assist in identifying the functional failures, causes of failures, and risk ranking which are linked to corrosion rates and the remaining life of the heat exchangers. Afefy (2010) [26] investigated the application of RCM methodology to the development of a maintenance plan for a steam-process plant. The proposed RCM spiced PM planning indicated that the system will enjoy about a 25.8% decrease in total labour cost, an 80% reduction in total downtime cost, and also about a 22.17% decrease in the annual spare parts cost for the proposed RCM-PM planning application. Ramli & Arffin (2012) [27] also carried out research on RCM in the schedule improvement of the automotive industry. The number of checklists in the body shop was reduced, and this resulted in a significant reduction in the operator's workload and prevented fraud by maintenance personnel. It was confirmed that the implementation of RCM provided a high level of success and the same methodology could be applied to equipment in other shops [25–27].

Tarar (2014) [28] carried out a study on RCM for rotating equipment through predictive maintenance. This paper evaluated the effectiveness of the existing maintenance strategy with optimization proposals. It showed the RCM process for a case study of paint booth fans process. The paper revealed that successful RCM implementation in any given industry can ensure improved performance to gain an edge over competitors in the global market. Recently, Emovon et al. (2018) [29] carried out a review on the development of more effective RCM tools for maintenance practices in plant systems for increased safety and efficiency. Some authors have pointed out the drawbacks of the risk priority number (RPN) as they established that RPN is not able to depict exactly the severity of some failure modes especially when certain factors such as economic cost and environmental impact are involved in the risk analysis [30]. Consequently, some other authors integrated the weighted aggregated product assessment (WASPAS) into RCM as an alternative for prioritizing the use of the RPN [31]. The technique was said to improve the effectiveness of RCM as well as in the selection of an optimal maintenance strategy for some industrial applications [32]. Further to the previous researches, this research seeks to implement the RCM for an individual section-forming machine (ISM) which is used in a glass bottle production company. RPN is considered the best option for the nature of the data collected for this study as some of the alternatives are found to require a maintenance data collection pattern a little different from the conventional [28,29,33].

2. Materials and Methods

2.1. Components of Individual Section-Forming Machine (ISM)

The individual section-forming machine usually comprises even-numbered sections. Besides operating as a single machine, two machines can be connected in line. Furthermore, the number of working sections can be changed and the kiln delivery capacity is of fundamental importance. To produce special items, auxiliary mechanisms and equipment are available to be used on the machine, such as the single, double, triple, quadruple gob, blow–blow, press–blow, narrow neck press–blow processes, vacuum mold, and blow mold support, as well as special equipment for the different production processes [12]. A more flexible production system is at present available owing to the servo–feeder, gob servo–distributor, servo–pusher, and the electric shaft system for flexible lines.

2.2. Mechanism Selection Process

The criteria for the selection of the components are as follows:

- The frequency of downtime/failure of a component
- Type of components as to whether it is a mechanism or a variable
- Criticality of component failure
- Availability of technical description and maintenance guidelines for the component
- Information gathered from a questionnaire on the reliability of components.

2.3. Questionnaire Design for Individual Section-Forming Machine Maintenance Staff

In the course of the research, questionnaires were administered to all maintenance staff, key production crews, and forehearth staff of Beta Glass Plc. The company is located at Ogun State in Nigeria. They are specialized in the production of glass containers particularly bottles. The aim of the questionnaires was to investigate the machine functionality, capability, and reliability and also the distribution of roles in the maintenance department. The information used spans across 15 quarters between the year 2010 and 2014 (i.e., each report is compiled for three months) with each quarter labelled 1st to 15th.

2.4. Failure Risk Analysis

For each of the identified components of the ISM, the risk analysis for experiencing any form of failure was conducted based on the available data, using failure modes and effect analysis (FMEA), and also a downtime analysis of the components across the period was considered [34].

Step 1: Review all processes involved in getting the product.
Step 2: Highlight all possible failure modes.
Step 3: Exhaust all the possible effects of each failure mode.
Step 4: Assign ranking for the severity of each effect.
Step 5: Assign ranking for the probability of occurrence of each failure mode.
Step 6: Assign ranking for ease of detection of each failure mode.
Step 7: Compute the risk priority number (RPN) for each of the failure modes.

The severity ranking (S), the occurrence ranking (O), and the detection ranking (D) used for the analysis are as shown in Tables 1–3.

$$\textbf{Risk Priority Number} = \textbf{Severity} \times \textbf{Occurrence} \times \textbf{Detection} \quad (5)$$

$$\textbf{RPN} = \textbf{S*O*D} \quad (6)$$

The mechanism input sources for FMEA is as follows:

- Questionnaires completed by maintenance staff.
- Downtime data showing details of failure which occurred.
- Working drawings of components.
- Maintenance instructions as provided by manufacturers.
- Failure modes and effects analysis of standard mechanical components.
- On field assembly and disassembly during repairs and diagnostics of fault.

Table 1. Ranking for the severity of each failure (S).

Definition	Rating
No Effect	1. None
Within specified limits	2. Very Minor
Downtime 0–10 min no defects	3. Minor
Downtime 10–30 min no defects	4. Very Low
Downtime 30–60 min,1 h of defects	5. Low
Downtime and defects 1–2 h	6. Moderate
Downtime > 4 h, defects 2–4 h.	7. High
Downtime > 8 h., defects > 4 h.	8. Very High
Affects personnel	9. Hazardous with warning
Safety/regulations	10. Hazardous w/o warning

Table 2. Occurrence ratings of failures/cycles (O).

Definition	Rating
<1/900,000, R(t) = 98%, MTBF = 50×	1. Very low
1/900,000, R(t) = 95% MTBF = 20×	2. Low
1/540,000, R(t) = 90% MTBF = 10×	3. Low
1/360,000, R(t) = 85% MTBF = 6×	4. Moderate
1/270,000, R(t) = 78% MTBF = 4×	5. Moderate
1/180,000, R(t) = 61% MTBF = 2×	6. Moderate
1/90,000, R(t) = 37% MTBF = Spec	7. High
1/36,000, R(t) = 19% MTBF = 0.6×	8. High
1/900, R(t) = 5% MTBF = 0.3×	9. Very High
>1/90, R(t) < 1% MTBF = 0.1×	10. Very High

Table 3. Failure detection ranking (D).

Definition	Rating
Almost Certain	1.
Very High	2.
High	3.
Moderate-High	4.
Moderate	5.
Low	6.
Very Low	7.
Fairly Remote	8.
Remote	9.
Very Remote	10.

2.5. Downtime Analysis

The downtime and the effective downtime for each quarter were collated for the following three (3) selected critical mechanisms using the data collected from the maintenance department of the company. The effective downtime for each mechanism in each quarter was collated with the financial loss as a result of the listed downtime. The cost of downtime is estimated by taking note of the production speed for each product as shown in Table 4 below.

$$V_b = V \times n \tag{7}$$

where n = number of gob; V_b = bottle speed; V = average production speed price.

Table 4. Cost analysis of downtime.

Product (Bottle Types)	Machine Speed (bpm)	Unit Price ($)	Bottle Speed (bpm)	Production Speed Price ($/m)
A	53	0.13	106	13.60
B	89	0.08	178	14.14
C	86	0.10	172	17.34
D	63	0.13	126	16.73
E	110	0.12	220	26.82
F	130	0.12	260	31.70
G	80	0.11	160	17.42
H	126	0.11	252	27.44
I	98	0.07	196	14.18
J	112	0.05	224	11.69
K	92	0.07	184	13.31
L	43	0.12	86	10.50
M	76	0.10	152	15.93
N	122	0.03	244	8.26

There were two gob mates in the plant, hence, the machine produces two bottles per unit delivery time. During the analysis, all electrical and non-direct control related issues were not considered.

3. Results and Discussion

Causes of failure were ranked, and then FMEAs were developed as well as the downtime analysis for the following selected critical components:

- Pusher cylinder

The function of the pusher mechanism is to transfer fully formed wares (glass bottles) from the pusher dead plate on to the machine conveyor where they are transferred for further processing.

- Plunger mechanism

The plunger mechanism is a very important mechanism on the individual section-forming machine performing the multiple and critical functions of forming the finish of the (mouth/tip) of the bottle and the initial shape of the bottle (parison) both on the blank side of the machine. When this is done, the parison is transferred to the final side by the neck ring mechanism for further processing.

- Ware transfer mechanism

The main function of the ware transfer is to transport fully formed bottles from the conveyor of the machine to the cross conveyor of the annealing Lehr.

3.1. FMEA for the Pusher Cylinder

Table 5 below assigned numbers (1–17) and Table 6, i.e., computation of failure modes and effect analysis (FMEA) for pusher cylinder had the following causes ranked by RPN.

Table 5. Causes of failure ranked 1 to 17 in a decreasing order of criticality for pusher cylinder.

S/N	Failure
1	Air drawn past rod seals during actuation with a RPN of 75
2	Bad control with a RPN of 6
3	Excessive loading with a RPN of 42
4	Excessive side loading with a RPN of 120
5	Excessive temperature with a RPN of 120
6	Fracture, material faults with a RPN of 36
7	High temperatures wear out with an RPN of 8
8	Inappropriate tightening, excessive temperature with a RPN of 90
9	Lubrication, wear out with a RPN of 284
10	Manufacturing error with a RPN of 126
11	Misalignment, inappropriate tightening with a RPN of 90
12	O-ring failure with a RPN of 80
13	Over tightening of 180
14	Seal leakage, piston cylinder ear with a RPN of 48
15	Side loading and piston wear, contaminants past rod seal with a RPN of 75
16	Stiction, binding with a RPN of 24
17	Vibration with a RPN of 180

Table 6. Computation of failure modes and effect analysis (FMEA) for pusher cylinder.

Function Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s)/Mechanism(s) of Failure	Occurrence	Detection	R. P. N.
PUSHER CYLINDER ASSEMBLY							
Transfer of hot glass wares from dead plate to silent chain of machine conveyor	Air leakage from cylinder assembly	In adequate stroke of pusher cylinder	4	O ring failure	4	5	80
	Wear of pusher fingers	Marks on wares	2	High temperature wears out	4	1	8
	Over travel in cylinder arm	Dents on bottles	2	bad control	3	1	6
	Broken bolt in pusher assembly	Over vibration and inappropriate operation	5	Misalignment, inappropriate tightening	9	2	90
	Work loose of bolt of pusher assembly	Excessive vibration, undesirable operation	5	In appropriate tightening, excessive temperature	9	2	90
	Wear of piston of the pusher assembly	Clearance and play in the assembly	4	Lubrication, wear out	5	7	140
	Piston ring broken and wear	Clearance and play in the assembly	4	Lubrication, wear out	6	6	144
	Internal Leakage	Loss/reduction of output force	5	Side loading and piston wear, contaminates past rod seal	3	5	75
	External Leakage	Loss/reduction of output force	4	Seal leakage, piston-cylinder ear	3	4	48
	Damaged rod seals	Contaminates entering pusher cylinder between shaft and cylinder	5	Excessive side loading	4	6	120
	Spurious position change	Loss of output control or incorrect signal transmission	3	Stiction, binding	2	4	24
	Jamming, seizure	Loss of load control	3	Excessive loading	7	2	42
	Aeration	Damaged actuator and loss of seals	5	Air drawn past rod seals during actuation	3	5	75
	Flange failure	In operation	4	fracture, material faults	3	3	36
	Bush lose on shaft	Loose coupling	5	Vibration	6	6	180
	Damaged set screw of bushing	Bushing failure	5	Overtightening	6	6	180
	Plate surface uneven	Leakage	7	Manufacturing error	3	6	126
	Loose pusher finger work	Wares un-transferable	5	Excessive temperature	8	3	120

3.1.1. Discussion of Results for Pusher Cylinder

According to Figure 7, the highest RPN of 284 was due to Cause 9 which was worn due to lack of or insufficient lubrication (from Table 5) with a potential failure mode of a broken piston ring which will produce a primary effect of an internal leakage and the inappropriate movement of the pusher cylinder arm. The conducted RCM analysis also shows that inappropriate tightening (either too tight or too loose) of bolted parts accounts for the majority of the failures in the pusher cylinder. Excessive vibration as indicated in Cause 17 in Table 5 has the effect of bringing about work loosening of the assembled bolted joint or leading to Cause 13, i.e., overtightening of the part, thus, having the effect of inappropriate operation and also external leakages. A lesser RPN was observed for causes such as bad control and wear of pusher fingers due to high temperature and a hash working environment, because these failures have very low occurrence rates and were very detectable in cases in which they occurred. Figure 8 shows loss due to downtime of pusher cylinder across investigated periods, 14th quarter recorded highest monetary loss.

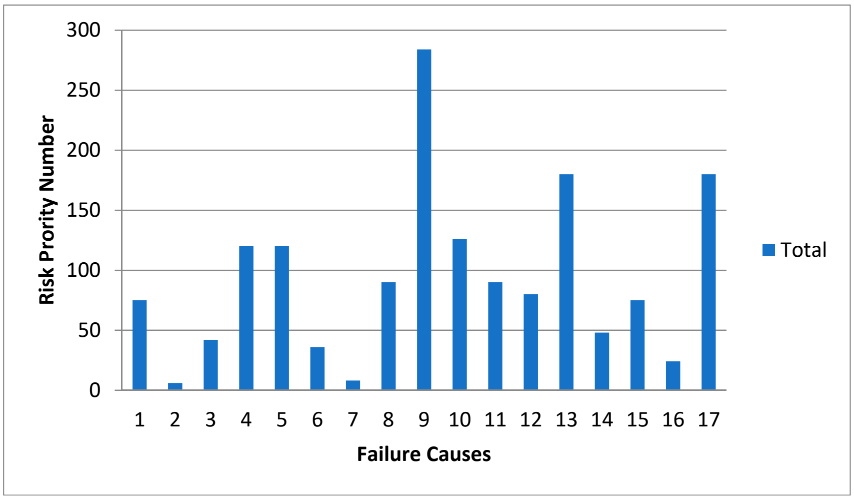

Figure 7. Distribution of failure causes to risk priority number (RPN) for pusher mechanism.

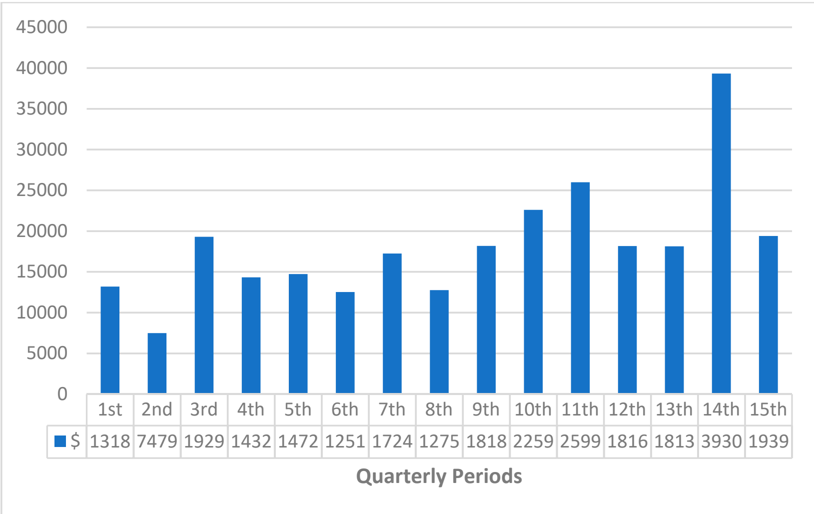

Figure 8. Loss due to downtime of pusher cylinder across investigated periods.

3.1.2. Downtime and Cost Analysis

The 14th period's data exhibits a conspicuous rise in downtime which was indicated with a loss of $39,308.97 while the time lowest is of the second quarterly period which means that the pusher cylinder was mostly functional through the three months of the second period.

3.2. FMEA for Plunger Mechanism

3.2.1. Discussion of Results for Plunger Mechanism

Table 7 displays the computation of FMEA for the plunger mechanism while Figure 9 shows the distribution of the assigned numbers (1–11) had the following causes ranked by risk. It is observed that the highest RPN of 225 was due to Cause 7 which is the presence of carbon residue in upper cylinder. This leads to the potential failure mode of the plunger as it becomes stuck during operation due to the absence of clearance. In addition, it can be seen that wear of the upper cylinder due to a failure mode of air leakage in piston assembly had an RPN of 196. This is followed by a mismanagement of excessive working pressure which makes the plunger supply hose connector pull off with an RPN of 192. A generally high RPN is observed for all failure causes of the plunder mechanism. This demonstrates the severity of the occurrence of such causes. Gasket flat had the lowest RPN of 84 due to failure modes of air leakage in inner mould during parison. This is because p ressure losses due to leakage can be compensated for by increasing the pressure. Even in cases of incomplete parison blowing, the effect is self-corrected during the final blowing process. Figure 10 Shows the distribution of failure causes to RPN for plunger mechanism.

Table 7. Computation of FMEA for the plunger mechanism.

Function Requirements	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) /Mechanism(s) of Failure	Occurrence	Detection	R. P. N.
Plunger Mechanism B962-3058M7							
Used for the formation of bottle finish and parison	Air leakage in piston assembly	Non-availability of vacuum	7	wear in upper cylinder	4	7	196
	Piston slow response	Internal leakage	5	piston ring wear	5	7	175
	Worn thread	Misalignment and vibration	5	inappropriate/unequal tighten	9	3	135
	Upper cylinder dent	Air leakage	6	contaminants/side loading	4	4	96
	Plunger down leakage	Improper settle blow	5	o ring creep	7	4	140
	bolt worloose	Misalignment during gob loading	4	excessive working pressure	9	4	144
	Plunger stuck	In operation of piston advance	5	carbon residue in upper cylinder	9	5	225
	Plunger connector pullout	In-operation due no absence of air supply	6	excessive working pressure	8	4	192
	Air leak form inner of the mold during gob loading	In appropriate formation of bottle finish	4	gasket flat	7	3	84
	Air leakage from piston shaft	Inability to form parison	6	nozzle gasket wear	3	5	90
	Piston guide bushing wear/loose	Internal leakage	6	cullet/contaminants presence	4	7	168

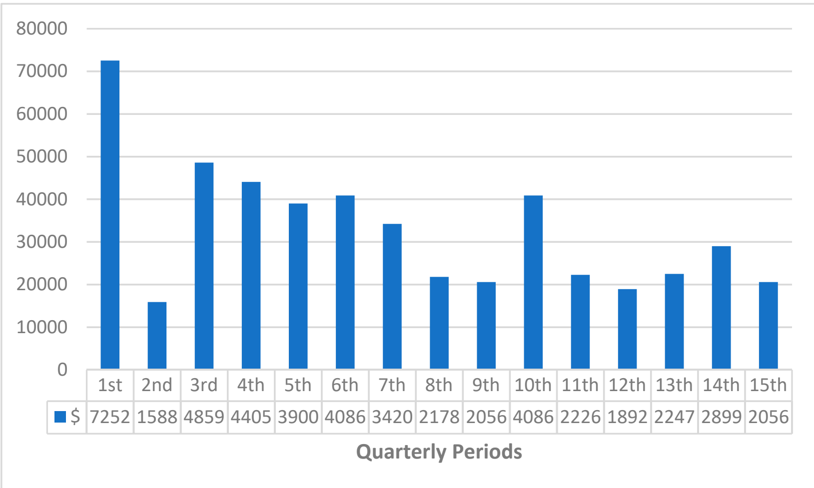

Figure 9. Loss in the cost of product not produced across quarterly periods for plunger mechanisms.

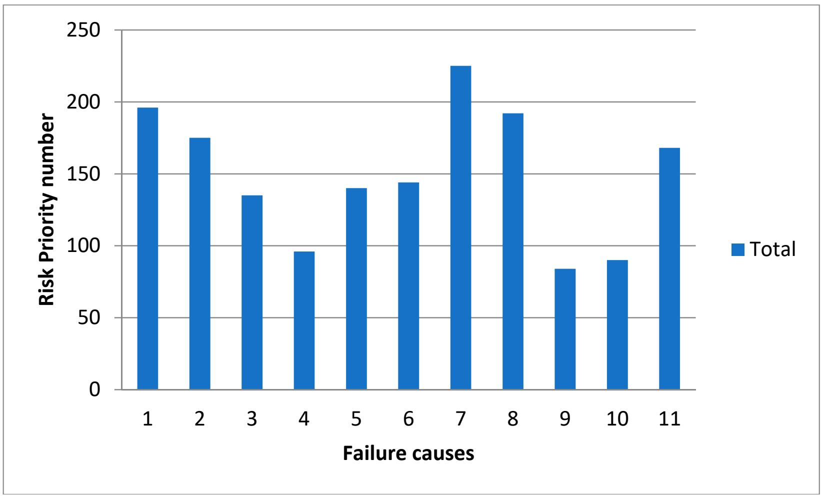

Figure 10. Distribution of failure causes to RPN for plunger mechanism.

3.2.2. Downtime/Cost Analysis

From the production records it was observed that the cost due to downtime was at the lowest in the 2nd quarter of the study period. However, the highest downtime cost loss was experienced in the 1st quarter of the observation period with a $72,521.81 loss in cost of products not produced as a result of the breakdown of the plunger mechanism.

3.3. Discussion of Results for Ware Transfer

From the distribution in Figure 11, assigned numbers (1–13) had the following causes ranked by RPN.

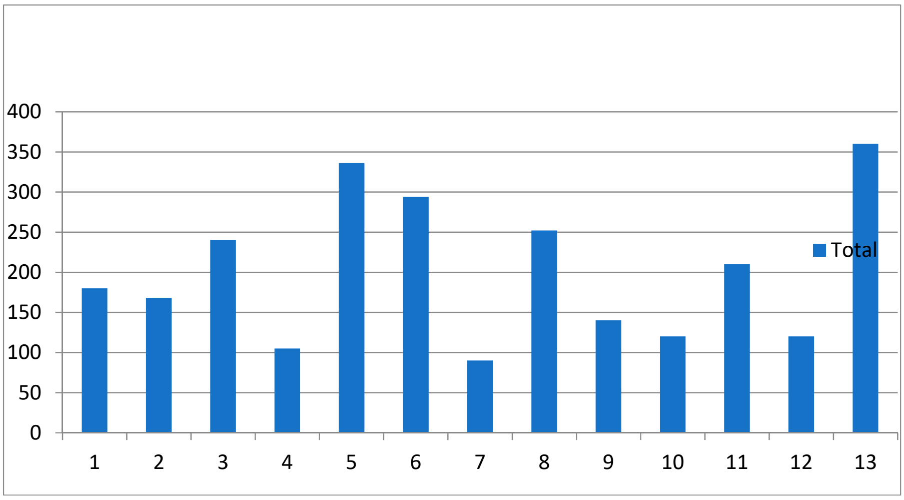

Figure 11. Distribution of failure causes to RPN for ware transfer mechanism.

The RCM analysis shows that the highest RPN of 360 was due to Cause 13 which is excessive heat and contamination. This has the potential failure mode of worn out of ware transfer fingers. Another high-temperature related failure which has a high probability of occurring with an RPN of 336 is identified with Cause 5 which is high temperature due to lack of lubricant in the ware transfer Mechanism. The failure mode associated with this defect is the clogging of the main bearing of the arms and linkages. Another high risk of the mechanism's failure was predicted to be the presence of contaminants in the lubricant of the bevel gear lubrication sump. This has a failure mode of abrasive wear of the bevel gears used in the transmission of motion for the shaft with the calculated RPN of 294.

A low RPN was observed in the case of detachment of bevel gear off on the shaft due to shear on the key. This is because the chances of this happening are rare and the failure mode is very easy to detect right from the early phase of installation and during maintenance activity. Another low-risk priority of 105 is linked with hooking of the cullet butt, this has a relatively high rate of occurrence rating of 7, but it is also very easy to detect as well as quite easy to correct, hence, a low severity rating number.

Downtime/Cost Analysis

Considering the broad spectrum of all the quarters in Figure 12, there exists a minimal production downtime loss due to ware transfer failure. The exceptions are an extreme loss of over $82,000 in the 10th quarter and a relatively similar loss of $62,293.28 in the quarter before. After which a relatively decreasing trend is shown in the loss associated with downtime from the 11th quarter of the observation period until the 15th.

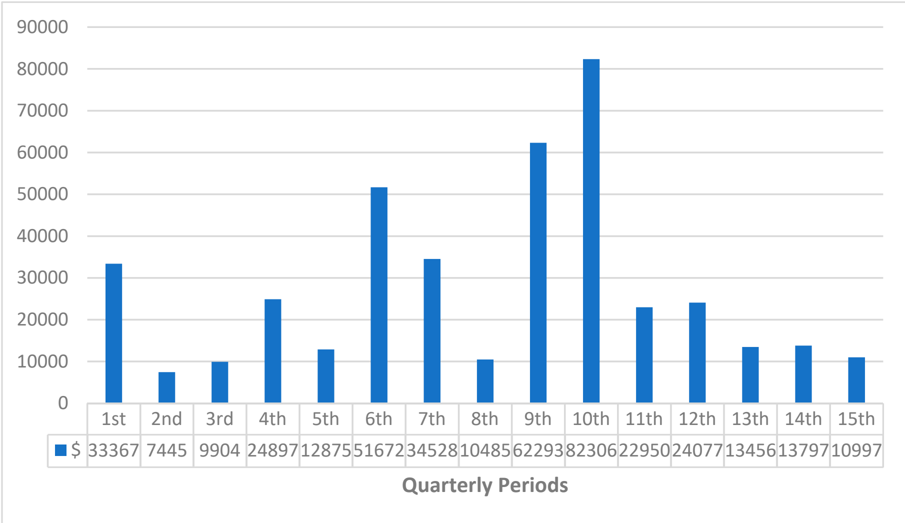

Figure 12. Loss in the cost of product not produced across the observed quarterly periods for ware transfer mechanism.

4. Conclusions and Recommendation

4.1. Suggestion for the Improved Reliability of the Pusher Assembly

Implementation of the selective run to failure, preventive maintenance, and precision maintenance respectively will lead to lower downtime cost and higher reliability of the pusher assembly. Through careful analysis of all the components of the pusher assembly, it was observed that most of the failure that occurs is due to random causes and over stress except all seals and piston rings. Use of precision maintenance requires that all bolts on the assembly should be locked with equal and right torque. In addition, the use of quality bolts and nuts will help reduce failure due to work loosening and bolt breakage (shear) and, thus, will go a long way to save cost due to unproduced products. Avoiding reuse as much as possible but rather using adhesives is recommended. A redesigning of the pusher finger support is suggested on the basis of material selection since its excessive expansion causes the pusher finger bolts to work loose and misalign. A metalogical research should be done to attain a long-lasting material for the pusher that can sustain the working condition better than carbon steel. Experimental research on casehardening by heat treatment could be a solution. The oilers on all pusher assembly must be reinstalled, and frequent cleaning of both the oilers and the cylinder shaft needs to be carried out to avoid accumulation of carbon and dirt which blocks the oilers and makes the cylinder shaft stick. The use of some high technology like acoustic signals, vibration analyser, current signature analysis, and thermal imaging to enhance effective monitoring for early fault diagnosis in the pusher cylinder, plunger mechanism, and ware transfer is highly recommended [35–39]. The costs of deploying these monitoring devices will be easily recouped from the significant reduction in downtime that will occur [37].

4.2. Failure Reporting and Analysis Recommendation

All recorded downtime on individual sections should not be divided by the total number of sections on the particular machine. Dividing the downtime recorded by the number of sections assumes that the other sections compensate for the failed section by producing more. Since this is not so, the key performance indicator (KPI) for each machine line should be calculated individually. There is the need for a better failure reporting discipline to be implemented in the department. However, this involves input from the workshop floor on failure causes that are not be determined on the machine. This will help in completing the FMEA table more accurately, which will result in carrying out a more detailed failure analysis [40].

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