JJMIE

Volume 13, Number 3, October. 2019
ISSN 1995-6665
Pages 175 - 190

Jordan Journal of Mechanical and Industrial Engineering

A New Framework of Reliability Centered Maintenance

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Received 28 July. 2018

Abstract

In this paper, a novel framework of reliability centered maintenance (RCM) is proposed. The objective of this RCM model is to overcome the shortcomings of the existing RCM models. Current RCM models neither propose any actions with non-critical equipment nor propose any maintenance metrics. Moreover, they do not present maintenance work order flow. Both the classical and streamlined RCM models are adopted to formulate the proposed model to be more effective and efficient, i.e. it is focusing on the main functions of the system for the sake of preventing or eliminating the maintenance actions that are not necessary and identify effective maintenance tasks. In addition, a general Excel-based algorithm is proposed to perform criticality analysis and classification of machines/equipment into different categories. The proposed framework of RCM has been applied and evaluated in a real case study; namely is Fayoum Sugar Works Company in Egypt which produces Sugar. The results of applying RCM on A-Sugar line show that corrective and preventive maintenance downtime decreased by 55.77% and 52.17%, respectively. This reduction in downtimes leads to a saving in the total maintenance cost by 52.17%, which means that the proposed RCM saved about 6.19×106 L. E (Egyptian Pound) in total maintenance cost. Moreover, the results reveal that the availability increase from 57.1% to 90.74% and reliability increased from 99.73% to 99.88% as well.

Keywords: RCM, Availability, Maintenance metrics, Framework;

1. Introduction

Over the last twenty years, maintenance has changed. The changes are due to a huge increase in the number and variety of facilities (plant and equipment) that must be maintained throughout the world, more complex designs, new maintenance techniques and changing views on maintenance organization and responsibilities. RCM is a systematic approach to determine the maintenance requirements of plant and equipment in its operation [1]. It employs preventive maintenance, predictive maintenance (PdM), real-time monitoring (RTM), run to failure and proactive maintenance. These techniques are an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with a minimum of maintenance [2]. The aim of RCM is to create such maintenance strategy that helps minimize the total operating costs while increasing reliability of the system [3]. Diego Piasson et al [4] introduces a new approach for reliability-centered maintenance programs in electric power distribution systems based on a multi-objective genetic algorithm. A framework for application of reliability centered maintenance in the lead oxide production system was studied by Nafis Ahmad et al [5]. Implementation of failure mode and effect criticality analysis (FMECA) and fishbone techniques in reliability centred maintenance planning presented by Tamer El-Dogdog et al [6]. RCM analysis of process equipment is studied by Majid et al [8]. This study focused on RCM analysis applied to process equipment with heat exchangers as a case study. Islam [9] introduced maintenance planning based on computer-aided preventive maintenance policy. Selvik and Aven [10] explained a framework for reliability and risk centered maintenance. The purpose of their paper is to motivate Reliability and Risk Centered Maintenance (RRCM) methodology and describes its main features.

An expert system for reliability- centered maintenance in the chemical industry presented by Fonseca and Knapp [11]. Dacheng et al [12] explained study and application of reliability-centered Maintenance considering radical maintenance. The researchers in this paper made a combination of radical maintenance (RM) and traditional RCM to improve the quality of maintenance strategies. Strategic maintenance-management in Nigerian industries was discussed by Mark et al. [13]. Implementation of the RCM methodology on the example of city waterworks is introduced by Zoran Petrović et al [14]. Dawane and

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Sedani introduced to study and investigations of RCM methodology in the manufacturing industry to minimize breakdown maintenance [15]. A framework for identification of maintenance significant items in reliability centered maintenance introduced by Yang Tang et al [16]. Samuel et al [17] investigated RCM study for an individual section-forming machine. Effectiveness of RCM program for power transformer is discussed by Burnet O'Brien Mkandawire et al [18]. In our previous works, Islam et al [19] investigated a model of reliability, availability, and maintainability (RAM) for industrial systems evaluations and implementation of framework RCM Made Simple approach is introduced [20].

In this section, we have reviewed various maintenance types applied to manufacturing and process industries. Most of the researchers have focused on classic RCM. Some researchers used software and others didn't. All results lead to the importance of the planned maintenance and preference of RCM. These become important issues in situations when applied the proposed framework RCM instead of classic RCM to a real case study. Moreover, excel program is used to perform maintenance program that would minimize maintenance cost and improve system availability and reliability of industrial processes. It is used in criticality analysis, functional failure analysis, and FMECA.

In this paper, a proposed framework of RCM model is presented to overcome some RCM classic shortcomings, such as no action for non-critical equipment, non-taking maintenance metrics, and not including maintenance work order flow. Furthermore, RCM classic should consider all factors that lead to failures, this increases the maintenance downtime. It should be noted that the major contribution of this work is to develop the framework of RCM implementation from which analysis of maintenance metrics and downtime metrics. Integrating between RCM Group and maintenance group to overcome some shortcoming in maintenance tasks leads to improvement in maintenance effectiveness and maintenance key performance indicators (KPIs). The proposed RCM and framework of RCM implementation has been applied and evaluated in a real industrial process, illustrating the effectiveness of the proposed RCM.

In addition, the framework of proposed RCM methodology describes all necessary steps thoroughly. This detailed description does not exist in classic RCM and is not clear in standard RCM. It selects the critical items based on system functions and functional failures analysis besides the failure history analysis, which helps the readers and researchers to implement the RCM in general. As for the difference between framework of proposed RCM methodology and the standard RCM technique, the standard RCM technique does not clarify the methodology of implementation.

2. Proposed RCM Model

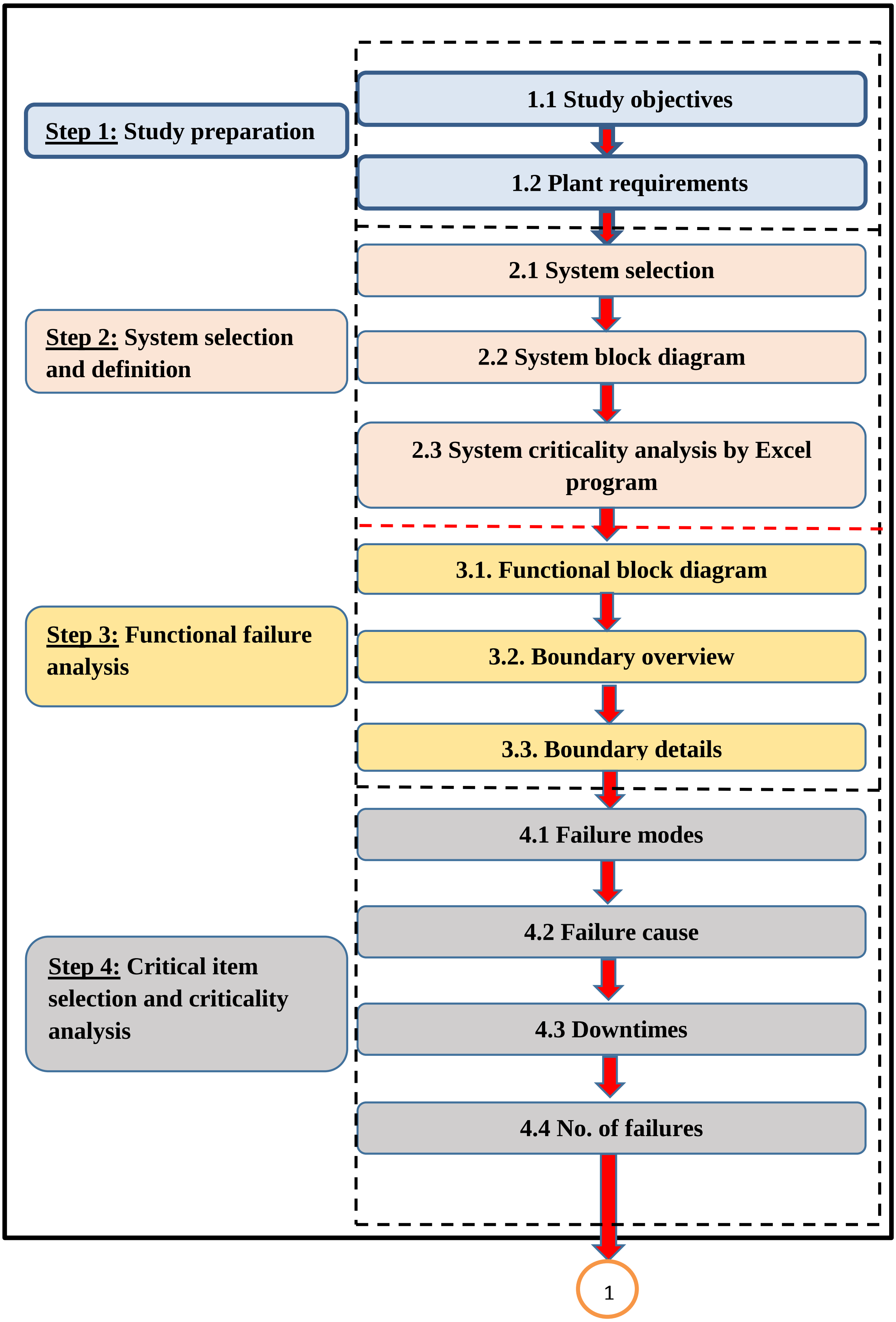
The proposed RCM methodology steps are discussed in addition to some of the analysis tools used in the real case study and applied in large industrial processes as follows:

1. Study preparation.
2. System selection and definition
3. Functional failure analysis (FFA)
4. Critical item selection and criticality analysis.
5. Data collection and analysis
6. Failure mode and effect criticality analysis (FMECA)
7. Logic tree analysis (LTA)
8. Selection of maintenance actions
9. Determination of maintenance intervals
10. Default action for non-critical equipment
11. Planned maintenance comparison
12. Framework of RCM Implementation.

Figure 1 shows that the proposed policy of RCM starting with study preparation of system works plant then select the most important plant, defined its boundary and critical equipment selected by applying criticality analysis. Functional block diagram (FBD) for the plant is carried out. All critical equipment failures in last years collected and analysed with respect to failures and downtime. Why-Why technique is used to analyse critical item failures. FMECA is carried on for failures, then LTA applied to select the suitable maintenance approach for each failure and used in maintenance action selection. After that, the default action for non-critical items is illustrated and planned maintenance comparison is performed. Finally, a proposed RCM plan is implemented and gets results.

2.1. Study Preparation

In this step, a proposed RCM project group is established. The project group must define and clarify the scope and the objectives of the analysis. RCM project group must define and clarify the objectives and the scope of the analysis.


Step 1: Study preparation
1.1 Study objectives
1.2 Plant requirements
Step 2: System selection and definition
2.1 System selection
2.2 System block diagram
2.3 System criticality analysis by Excel program
Step 3: Functional failure analysis
3.1. Functional block diagram
3.2. Boundary overview
3.3. Boundary details
Step 4: Critical item selection and criticality analysis
4.1 Failure modes
4.2 Failure cause
4.3 Downtimes
4.4 No. of failures
1

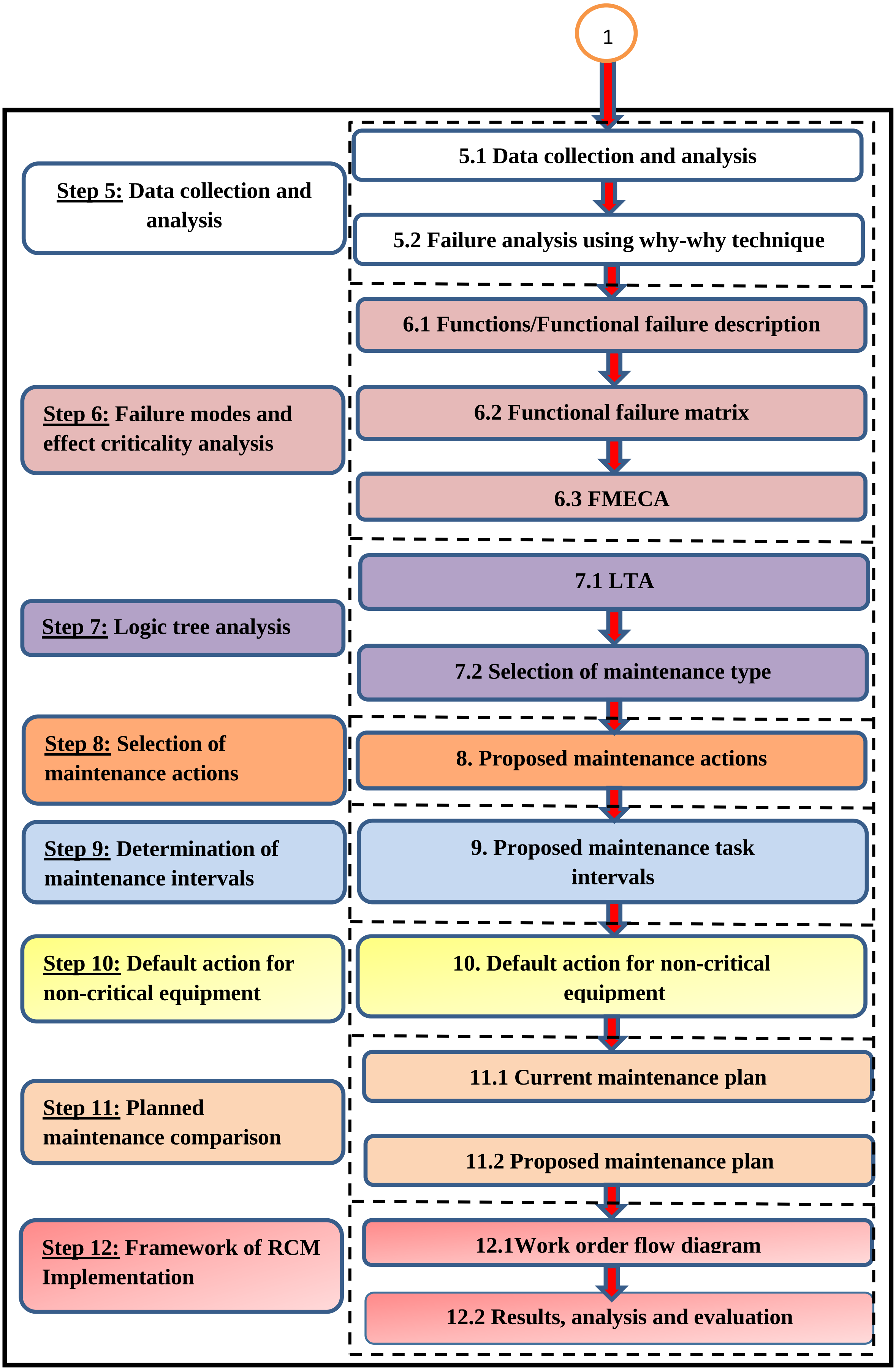


Figure 1. Framework of proposed RCM methodology

2.2. System Selection and Definition

A system is defined as a group of equipment, components, or facilities that support an operational function. These operational functions are identified by criticality analysis (See Figure 2) [21].

2.3. Functional Failure Analysis (FFA)

Functional failures explain the ways in which a subsystem or system can fail to meet the functional requirements designed for the equipment [22]. The main objectives of FFA step are as follows;

- To identify the ways in which the system might fail to function
- To list input interfaces necessary for the system to operate.
- To describe and identify the system's required functions and performance criteria.

2.4. Functional Block Diagrams (FBD).

The FBD displays all components of a system, their functional relationships to one another, and in and out interfaces with other systems. The FBD is also useful as a basis for the FMECA in the RCM analysis process. It is generally not required to establish the FBD for all the system functions. The diagrams are, however, efficient tools to illustrate the input interfaces to a function.

2.5. Root Cause Failure Analysis

The goal of RCFA is to identify the contributing causal factors that have led to a performance problem. Also finding the real cause of the problem and dealing with it rather than simply continuing to deal with the symptoms. When problems occur, use the tools to understand and gain insight into the causes before making changes based on assumptions. [23]. A fishbone diagram is a visual way to look at cause and effect. It is a more structured approach than some other tools available for brainstorming causes of a problem (e.g., the Five Whys tool). Five whys strategy worksheet is introduced in table 1.

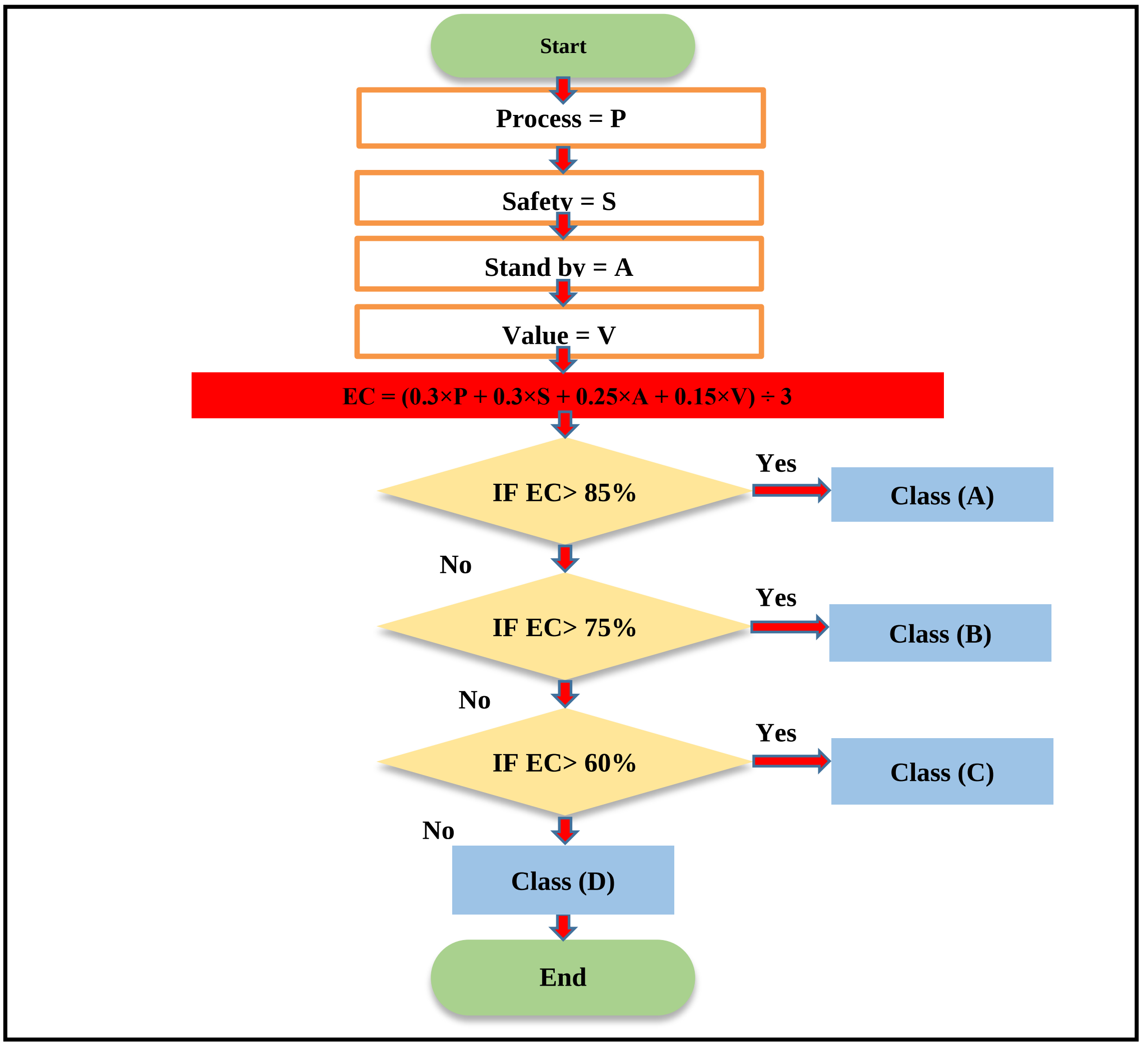


Figure 2. General algorithm diagram used to calculate the criticality value [21]

2.6. Critical Item Selection

The objective of this step is to identify the analysis items that are potentially critical with respect to the functional failures identified in FFA step.

2.7. Data Collection and Analysis

The purpose of this step is to establish a basis for both the qualitative and quantitative analysis. The data necessary for the RCM analysis may be categorized into the following three groups:

- Group 1: Design data
- Group 2: Operational and failure data
- Group 3: Reliability data

2.8. FMECA

FMECA is the procedure, which consolidates a failure mode and effects analysis and a criticality analysis. It is utilized to document and identify the functions, functional failures, failure modes and failure effects of an item. Besides that, it determines the significance of functional failures in terms of operations, economics, safety, and environment. It also classifies the severity of every failure effect according to criteria of established severity classification and provides failure rate information.

2.9. Logic Tree Analysis

LTA process is the step used to determine the most applicable, cost-effective maintenance tasks for a component [23]. LTA is used to assess the relationship between failure mode and each part with a high maintenance priority [24]. The input to LTA is the failure modes from the FMECA. The main idea is for each failure mode to decide whether a preventive maintenance task is suitable, or it will be best to let the item deliberately run to failure and afterward carry out a corrective maintenance task. RCM logic tree is shown in figure 3.

2.10. Selection of Maintenance Actions

The maintenance task selection process uses various forms of logical decision making to arrive at conclusions in a systematic manner. The outcomes can include:

- Preventive maintenance.
- Condition monitoring.
- Inspection and functional testing.
- Run to Failure.

2.11. Determination of Maintenance Intervals

Maintenance actions are divided into corrective maintenance (CM) and preventive maintenance (PM). CM actions are unscheduled and are intended to restore a system from a failed state to a working state through either replacement or repair of failed components. On the other hand, PM is scheduled active and can be carried out either to reduce the likelihood of a failure or to improve the availability and reliability of the system [25].

2.12. Default Action for Non-Critical Equipment

It is important to include the non-critical machines or items in the maintenance policy. The catalogues of these machines are enough to prevent sudden failures because of the high total cost of maintenance. The sudden failure of these machines has no effect on production and safety.

2.13. Planned Maintenance Comparison

The outputs of the analysis will result in a change to the maintenance program. It is important that such changes are consistent with the maintenance philosophy of the plant and with regulatory and social obligations. For this reason, it is important that the process and it is outcomes be subjected to a final review.

2.14. Framework of RCM Implementation

As shown in figure 4, framework of RCM Implementation is presented. Once the proposed framework of RCM implementation approved, the final step is to implement the proposed maintenance tasks in a real case study. The maintenance tasks are then fed into suitable maintenance planning and control systems, while revised operating procedures are usually incorporated into standard operating procedure manuals. Furthermore, the framework includes maintenance metrics such as mean time between failures (MTBF), mean time to repair and mean downtime.

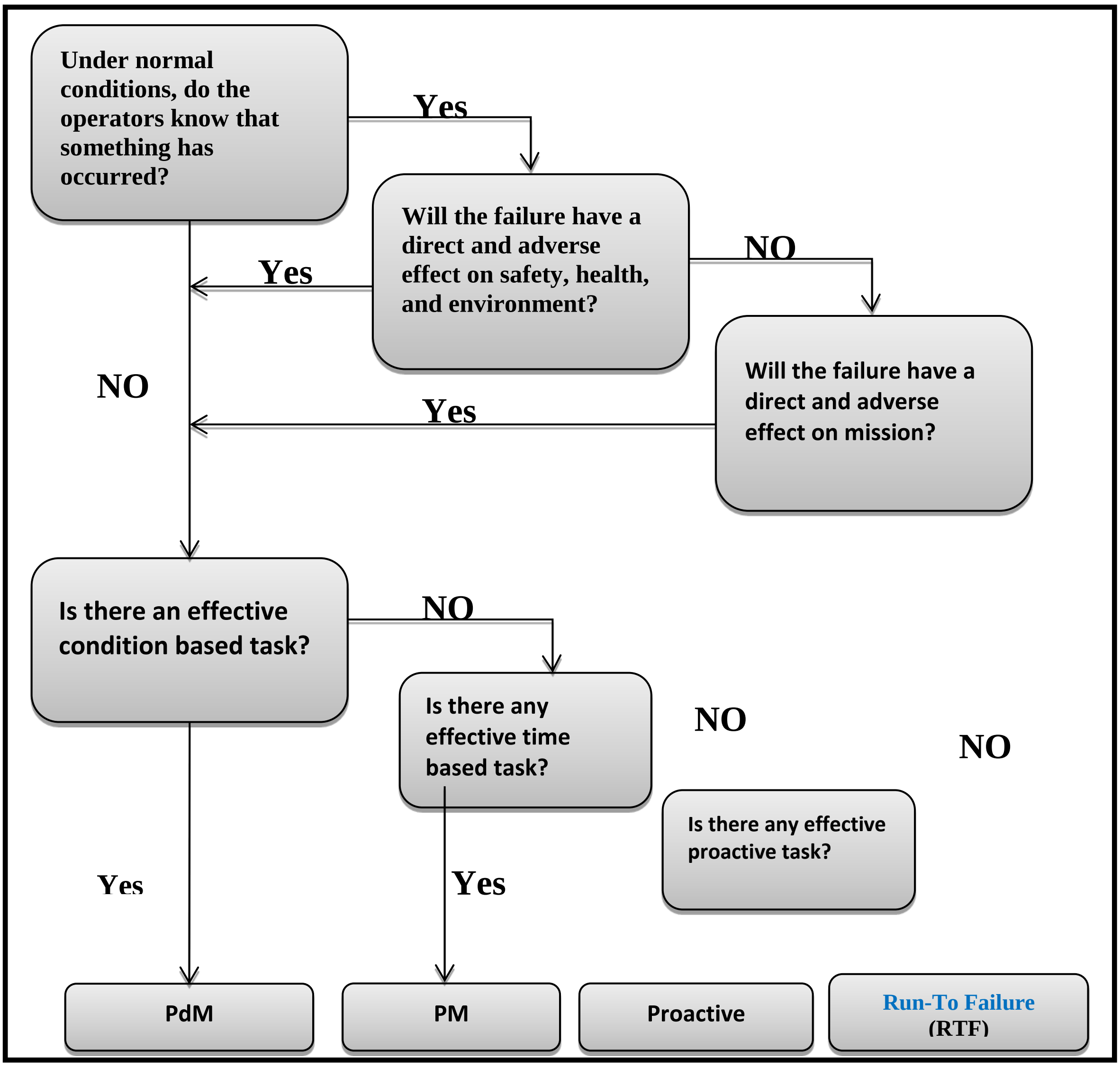


Figure 3. RCM logic tree

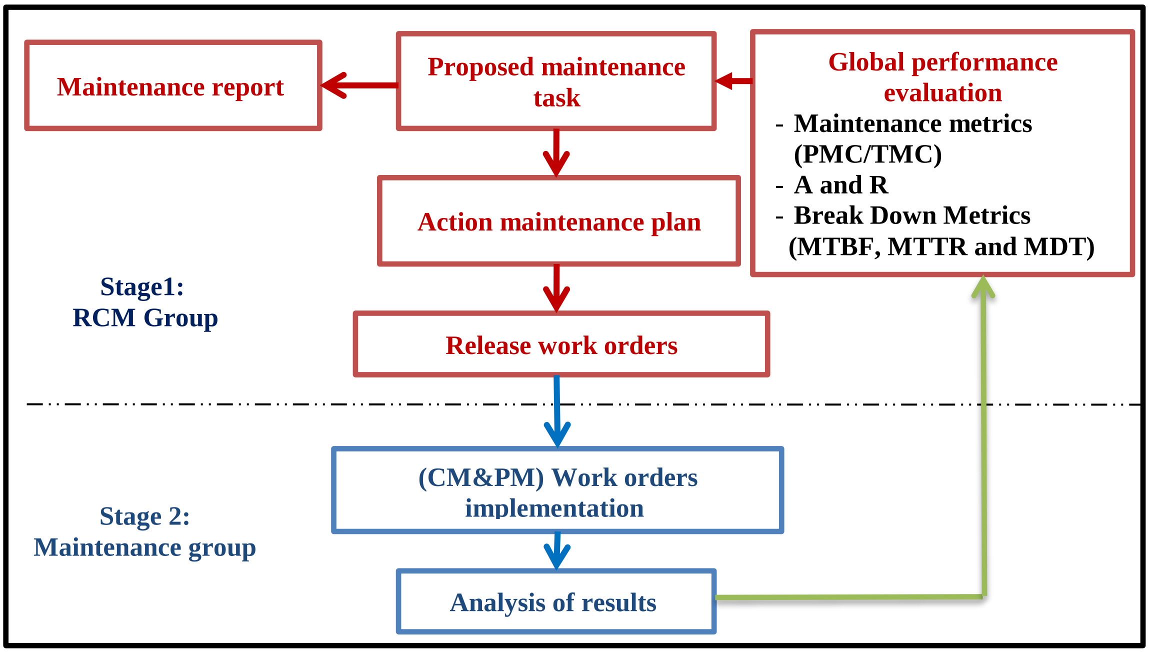


Figure 4. Framework of RCM Implementation

3. Modeling of Availability and Mean Time between Failure

Availability is the probability that a material, component, equipment, system or process is in its intended functional condition at a given time and therefore is either in use or capable of being used in a stable environment [9 &28]. It is a measure of the degree to which an item is in an operable state and can be committed at the start of a mission when the mission is called for at an unknown point in time and it is defined mathematically as:

$$A=\frac{MTBF}{(MTBF+MDT)} \quad (1)$$

$$MTBF=\frac{AT-(N_f \times MDT)}{N_f} \quad (2)$$

$$\text{Failure rate } (\lambda)=\frac{N_f}{AT-(N_f \times MDT)} \quad (3)$$

Where, N_f is the number of failure, AT is the available time, MTBF is mean time between failure and MDT is mean downtime.

4. Modeling of Reliability

The characteristic of an item expressed by the probability that it will perform a required function under a stated condition for a stated period of time [28] and it is defined mathematically as:

$$R=\frac{\text{Planned time}-\text{Unplanned time}}{\text{Planned time}} \quad (4)$$

Where, planned time is the total operated time, and unplanned time is the total of corrective maintenance time.

5. Modeling of the Total Maintenance Cost

Total maintenance cost (TMC) can be calculated by the follow equation:

$$TMC = CMC + PMC + DTC \quad (5)$$

Where, CMC is the corrective maintenance cost, PMC is the preventive maintenance cost and DTC is the downtime cost.

6. Modeling of the PM Worker Size.

A specific formula is present to define the preventive maintenance worker size (WS_{PM}) as:

$$WSPM = MDa / WOC \quad (6)$$

Where, MD_a is the total preventive maintenance annual man-day, and W_{OC} is the workers operating conditions (day/year).

The total preventive maintenance annual man-day can be calculated as:

$$MDa= Fa \times tdu \times Wn \quad (7)$$

Where F_a is the annual frequency per preventive maintenance type, t_{du} is the duration time, and W_n is the number of workers per preventive maintenance type.

7. Case study

The present study has been applied for the practical Sugar-end plant of the Fayoum Sugar Works Company, EL-Fayoum, Egypt. The main products of the company are Sugar, Molasses and Beet Pulp. The main objective of the sugar-end plant is to crystallize sucrose present in the thick juice to granulated-refined sugar and molasses.

7.1. System Block Diagram

As shown in figure 5, the block diagram of Fayoum Sugar Works Company is introduced. This figure shows the main equipment of the system. It shows that the process flow of juice between equipment of the A-sugar line.

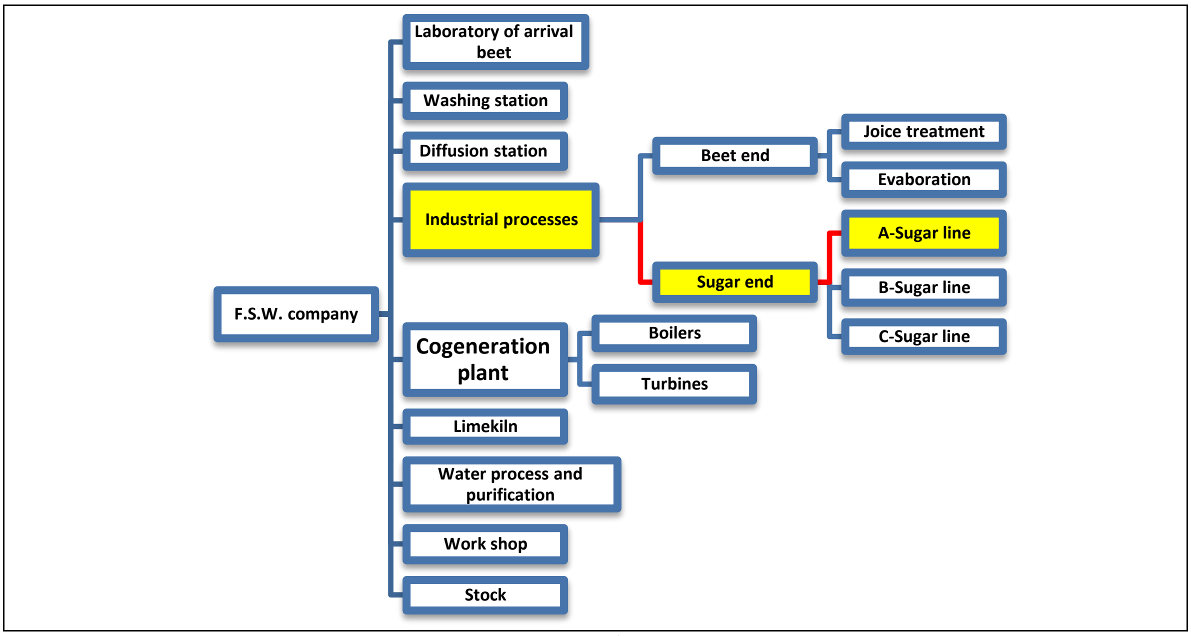


Figure 5. Block diagram of FSW Company.

7.2. System Criticality Analysis

General algorithm diagram used to calculate the criticality value (see figure 2). This algorithm shows the calculation steps of the equipment criticality [2]. Excel program established to perform criticality analysis for system equipment and grouping classified. Table 1 presents the result of system criticality and equipment selection

Table 1. System criticality analysis and equipment selection

Item No.	Component	P	S	A	V	EC%	Group
4.11	Wet sugar Bucket elevator	3	2	3	3	90	A
4.1	Sugar dryer	3	2	3	3	90	A
16.15	Wet sugar Vibrator (Gras hopper)	3	2	3	2	85	B
4.9	Dry sugar Bucket elevator	3	2	3	2	85	B
16.01	A-Feed Solution Tank	3	1	3	2	75	B
16.13	A-Sugar Distributor	3	1	3	2	75	B
16.04	A-Seed pump F500	2	2	3	1	70	C
4.12	Wet sugar Conveyor	3	1	3	1	70	C
4.8	Dry sugar Conveyor "dryer exiting"	3	1	3	1	70	C
4.08	Wet sugar Conveyor "dryer entering"	3	1	3	1	70	C
16.11	A-Massecuite pump F1000	2	1	3	2	65	C
4.16	Standard liquor tank	2	1	3	1	60	C
16.14	Centrifugal machineG1500 for A-Sugar No.1~6	2	2	1	2	58.3	D
16.05	A-Feed Solution Pump No.1, 2	2	2	1	2	58.3	D
16.02	A-Seed Pan	2	1	2	2	56.67	D
4.7	Dry sugar Vibrator	2	1	2	2	56.67	D
4.10	Fin Fan	1	1	3	2	55	D
16.06	A-VKT	2	1	1	3	53.3	D
16.03	A-Seed receiver tank	2	1	2	1	51.67	D
17.01	Under Scales conveyor (line No.1, 2, 3, 4)	1	2	2	1	51.67	D
17.02	Delivery conveyor (line No.1, 2, 3, 4)	1	2	2	1	51.67	D
16.19	A-Wash syrup Pump No.1, 2	1	2	1	2	48.3	D
4.18	Standard liquor tank Pump No.1, 2	1	1	1	1	33.3	D

7.3. Functional Block Diagram (FBD) of System

FBD of the system is shown in figure 6. It is the relation between equipment of the A-Sugar line of sugar end plant, which selected as a system to applied proposed RCM on it.

7.4. Critical Items Selection

Identifying the most critical equipment and the critical items in the system is based on total downtime. Table 2 shows downtimes and number of failures for the system. In addition to, the downtimes and number of failures for components of system equipment are introduced in table 3 and figure 7.

Table 2. Relation between no. of failures and downtimes for A-sugar line equipment

Equipment	No. of failure	Downtime (Min.)	% of downtime
Wet Sugar bucket elevator	2	90	5.14
Sugar dryer	2	55	3.14
Wet Sugar vibrator	9	343	19.60
Dry sugar Bucket elevator	8	165	9.43
A-Feed Solution tank	1	34	1.94
A-Seed pump F500	4	620	35.43
Wet sugar Conveyor	4	90	5.14
Dryer entering conveyor	3	60	3.43
Dryer exiting conveyor	4	93	5.31
A-Massecuite pump (F1000)	2	200	11.43
Total	39	1750	100

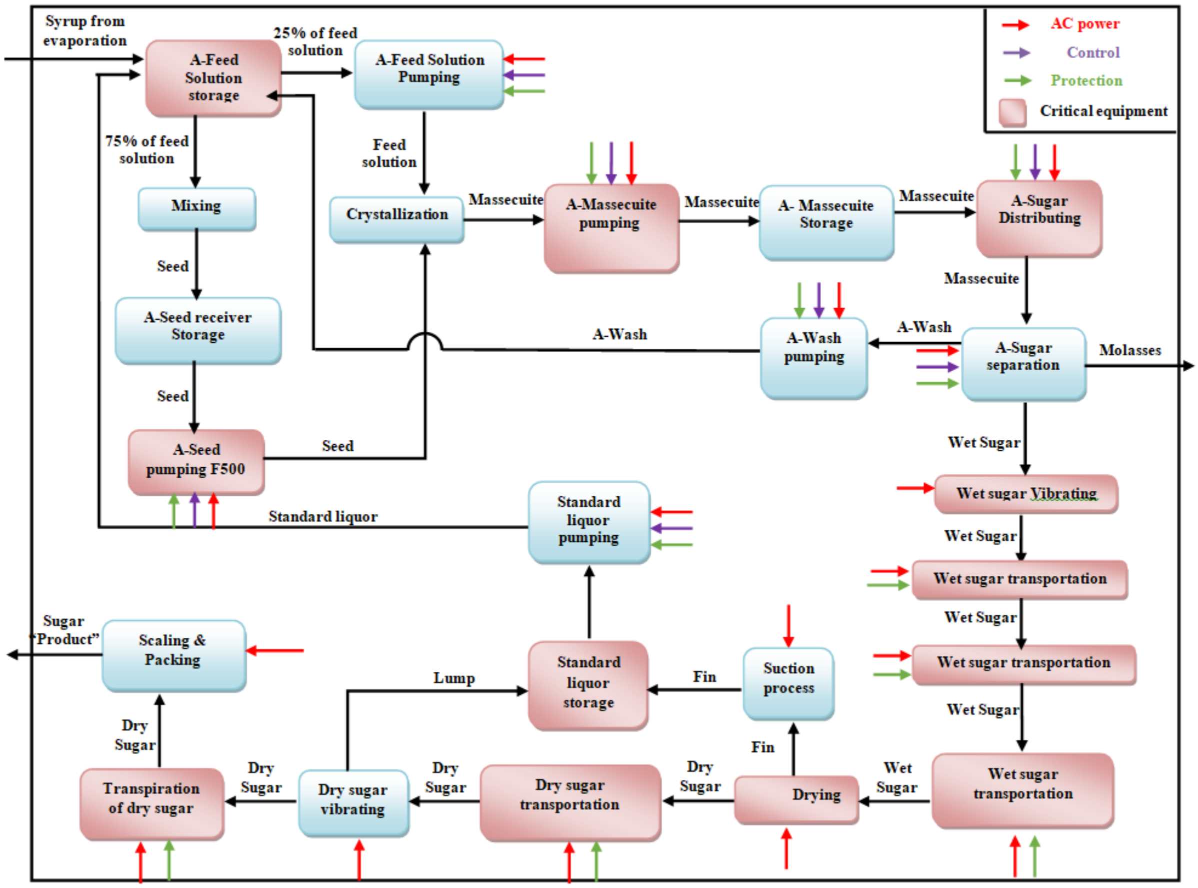


Figure 6. Functional block diagram of A-Sugar line End plant

Table 3. Relation between no. of failures, downtimes and MTBF for components of A-sugar line equipment.

Equipment	Component	No. of failure	Downtime (Min.)	% of downtime	MTBF (hr.)
Wet Sugar bucket elevator	Motor (over load)	1	60	3.49	180
	Level device	1	30	1.74	180
Sugar dryer	Motor (over load)	1	25	1.45	180
	Level device	1	30	1.74	180
Wet Sugar vibrator	Trough	7	298	17.33	25.7
	Bolts	1	15	0.87	3
Dry sugar Bucket elevator	Main conveyor (elongation)	6	90	5.23	30
	Main conveyor (slipping)	1	45	2.62	180
	Level device	1	30	1.74	180
A-Feed Solution tank	Motor	1	34	1.98	180
A-Seed pump F500	Piston clearance	4	620	36.05	45
Wet sugar Conveyor	Main conveyor (slipping)	1	15	0.87	180
	Motor's conveyors	2	60	3.49	90
	Rollers	1	15	0.87	180
Dryer entering conveyor	Motor's conveyors	1	30	1.74	180
	Rollers	2	30	1.74	90
Dryer exiting conveyor	Motor's conveyors	2	58	3.37	90
	Main conveyor (elongation)	1	20	1.16	180
	Rollers	1	15	0.87	180
A-Massecuite pump (F1000)	Piston clearance	1	180	10.47	180
	Spring	1	20	1.16	180

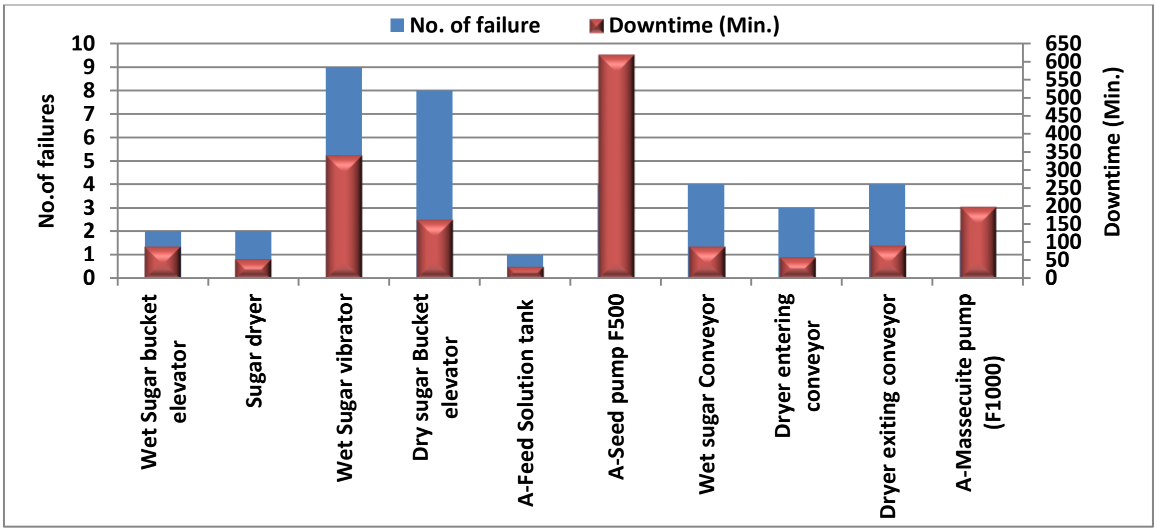


Figure 7. Relation between no. of failures and downtime

7.5. Failure Analysis Using Why-Why Technique

Tables from (4) to (8) shows that the equipment and its function, failure mode and levels analysis.

Table 4. Failure modes at different level of details for wet sugar vibrator

- Equipment: Wet Sugar vibrator
- Function: Transfer and distribute sugar from Centrifuges to wet sugar conveyor
- Failure mode: High sound

Level 1	Level 2	Level 3	Level 4	Level5
Trough unit operate with high vibration level	Crack in Trough	Over load	Sequence of centrifuges isn't correct	Fault in operation
		Material of trough		
	Bolts looseness	Assembly error	Poor maintenance	

Table 5. Failure modes at different level of details for dry sugar bucket elevator

- Equipment: Dry sugar Bucket elevator
- Function: Transfer and distribute sugar from Centrifuges to wet sugar conveyor
- Failure mode: Irregular feeding with low capacity and low speed

Level 1	Level 2	Level 3	Level 4	Level5
Main conveyor Slipping	Loosens of conveyor	Elongation of conveyor	Tension	Assembly error
Main conveyor Rupture	Slipping of conveyor and not stopped	Sensor not working		

Table 6. Failure modes at different level of details for A-Seed pump F500

- Equipment: A-Seed pump F500
- Function: Pumps are employed for delivery massecuite
- Failure mode: Delivery massecuite by flow rate less than specified

Level 1	Level 2	Level 3	Level 4	Level5
Piston high clearance	Wear	Erosion	Suspend solid	
Viscosity higher than specified	Low temperature	Fault in operation		
Line resistance too high	Fossilized sugar	Low temperature	Fault in operation	

Table 7. Failure modes at different level of details for A-Massecuite pump (F1000)

- Equipment: A-Massecuite pump (F1000)
- Function: Pumps are employed for delivery massecuite
- Failure mode: Low flow rate

Level 1	Level 2	Level 3	Level 4	Level5
Piston high clearance	Wear	Erosion	Suspend solid	
Viscosity higher than specified	Low temperature	Fault in operation		
Line resistance too high	Fossilized sugar	Low temperature	Fault in operation	

Table 8. Failure modes at different level of details for dryer exiting conveyor

- Equipment: Dryer exiting conveyor
- Function: Conveys dry sugar from dryer
- Failure mode: Fails to transfer some sugar

Level 1	Level 2	Level 3	Level 4	Level5
Motor's conveyors Consumed	High friction between pulley and conveyors	High tension	Poor maintenance	
Excessive wear on bottom side of belt.	Slippage between belt and drive pulley	Low tension	Assembly error	
			Conveyor elongated	

7.6. FMECA

FMECA work sheet represented in table 9, there are twelve failure modes to apply FMECA on it. FMECA shows the effect of every failure mode on the equipment, system and plant. In addition to, calculate risk priority number (RPN= S × O × D) of them. Where, S is the rank of the severity of the failure mode, O is the rank of the occurrence of the failure mode and D is the rank of the likelihood the failure will be detected.

7.7. Logic Tree Analysis

The LTA information of system is introduced in table10.

Table 9. FMECA worksheet

FF#	Equip. #	Equipment description	FM#	Failure mode	FC#	Failure cause	Failure effect			S	O	D	RPN
							Local	System	Plant				
3.1.1	3	Wet sugar vibrator	3.01	Crack in vibrator trough	03.01.1	Over load	High sound	Stopped	Stopped	5	8	8	320
			3.02	Loosening of bolts	03.02.1	Poor assembly	High sound	Stopped	Stopped	6	4	8	192
	4	Dry sugar Bucket elevator	4.01	Bearing deterioration	04.01.1	Age/wear out	Inoperative	Stopped	Stopped	3	4	6	72
			4.02	Belt slipping	04.02.2	Belt elongation	Slipping	Low performance rate	Reduced production	3	6	4	72
1.1.1	6	A-Seed pump F500	6.01	High piston clearance	06.01.1	Wear	Erratic pump operation	Reduced flow	Reduced production	3	3	6	54
			6.02	Bearing deterioration	06.02.1	Age/wear out	Erratic pump operation	Reduced flow	Reduced production	3	3	6	54
			6.03	Mechanical seal failed	06.03.1	Leakage	Trip	Low performance rate	low performance rate	3	5	5	75
3.1.1	9	Dryer exiting conveyor	9.01	Belt slip	09.01.1	Insufficient traction between the belt and pulley	Erratic operation	Reduced flow	Reduced production	5	3	4	60
				Belt elongation	09.01.2	High tension	Stopped	Stopped	Stopped	3	4	4	48
2.1.1	10	A-Massecuite pump (F1000)	10.01	High piston clearance	10.01.1	Wear	Erratic pump operation	Reduced flow	Reduced production	3	3	4	36
			10.02	Bearing deterioration	10.02.1	Age/wear out	Erratic pump operation	Reduced flow	Reduced production	3	3	4	36
			10.03	Mechanical seal failed	10.03.1	Leakage	Trip	Low performance rate	low performance rate	3	5	5	75

7.8. Selection of Maintenance Actions

In this step, set of actions performed to failure modes depends on the maintenance strategy type, which were selected in the past step by using LTA. Table 10 shows the proposed maintenance task.

7.9. Determination of Maintenance Intervals

In this step, selection of maintenance intervals for A-sugar line is carried out. After choosing the type of maintenance and tasks suitable for each failure mode it should be determined the suitable maintenance intervals daily, weekly, monthly or yearly and it depends on MTBF and RPN. In table 10, determination of maintenance intervals of A-sugar line presented.

7.10. Default Action for Non-Critical Equipment

A remaining question is what to do with the items that are not analyzed. For equipment already has a maintenance program, it is reasonable to continue this program. If there is no maintenance program the default action for is RTF based maintenance. The catalog troubleshooting analysis of these machines is very enough to follow it to prevent suddenly failures. The maintenance policy of non-critical equipment based on the catalog is very enough.

7.11. Planned Maintenance Comparison

After the task selection and determination of intervals has been completed and reviewed, the maintenance actions arising from the task selection between “process” and “compared” against the current maintenance practices. The purpose of this comparison is to identify the changes needed to the maintenance program and the impact on resources and other commitments. Comparison between current and proposed maintenance tasks are shown in table 10.

Table 10. Logic tree analysis, current and proposed maintenance task.

Failure mode	Failure cause	Source of Failure	LTA						Current maintenance task	Proposed maintenance		
			1	2	3	4	5	6		Maintenance type	Task	Interval
Crack in vibrator trough	Over load	Sequence of centrifuges isn’t correct	N	-	-	N	Y	-	RTF	PM	- Visual inspection - Check sequence - Welding cracks	W
Loosening of bolts	Poor assembly	Poor maintenance	N	-	-	N	N	Y	RTF	Proactive	Check &Retighten	M
Bearing deterioration	Age/wear out	Incorrect assembly	N	-	-	Y	-	-	RTF	PdM	Vibration measure	M
Belt slipping	Belt elongation	High tension	Y	N	Y	N	N	Y	RTF	Proactive	Check belt & tension	W
High piston clearance	Wear	Suspend solid	N	N	Y	N	Y	-	RTF	PdM	Flow rate measure	D
Bearing deterioration	Age/wear out	Incorrect assembly	N	-	-	Y	-	-	RTF	PdM	Vibration measure	M
Mechanical seal failed	leakage	Deterioration	Y	N	N	-	-	-	RTF	RTF	RTF	-
Belt slip	Insufficient traction between the belt and pulley	Incorrect assembly	N	-	-	N	N	Y	RTF	Proactive	Check belt & tension	W
Belt elongation	High tension	High tension	Y	N	Y	N	N	Y	RTF	Proactive	Check belt & tension	W
High piston clearance	Wear	Suspend solid	N	N	Y	N	Y	-	RTF	PdM	Flow rate measure	D
Bearing deterioration	Age/wear out	Incorrect assembly	N	-	-	Y	-	-	RTF	PdM	Vibration measure	M
Mechanical seal failed	leakage	Deterioration	Y	N	N	-	-	-	RTF	RTF	RTF	-

8. Results

Table 11 presents a comparison between results of before and after applying a proposed policy of RCM on the real case study. The result shows that corrective maintenance downtime decreased from 9.7 hours/year to 4.3 hours/year, therefore, its cost decreased from 3.88×10^6 L.E/year to 1.72×10^6 L.E/year. In addition, preventive maintenance is decreased from 20 hours/year to 10 hours/year and its cost decreased from 8×10^6 L.E./year to 3.97×10^6 L.E./year. This means that proposed RCM saved 6.19×10^6 L.E in total maintenance cost. System availability and reliability are improved as well. Availability is increased from 57.1% to 90.74% and reliability increased from 99.73% to 99.88%.

Figure 8 clearly depicts the difference between corrective maintenance downtime before and after applying a proposed policy of RCM in A-Sugar line. Also, the comparison between corrective maintenance cost before and after applying a proposed policy of RCM in A-Sugar line is presented in figure 9. As shown in figure 10, the comparison between preventive maintenance downtime before applying RCM and preventive maintenance downtime after applying a proposed policy of RCM for A-Sugar line is illustrated. Moreover, in figure 11, preventive maintenance cost before and after applying RCM for A-sugar line is discussed. Figure 12 shows the comparison of total maintenance cost before and after applying a proposed policy of RCM in A-Sugar line. As in figure 13, the availability analysis for A-sugar line is introduced and reliability analysis is presented in figure 14.

Table 11. Results of applying proposed RCM framework on A-Sugar line

No	Item	Before Current	After Applying RCM	Improvement %
	Corrective maintenance down time (hrs./year)	9.7	4.3	55.77
	Corrective maintenance cost $\times10^6$ (L.E/year)	3.89	1.72	55.77
	Preventive maintenance down time (hrs./year)	20	10	50
	Preventive maintenance cost$\times10^6$ (L.E/ year)	8	3.97	50.4
	Total maintenance cost $\times10^6$ (L.E)	11.89	5.69	52.17
	Availability (%)	57.1	90.47	36.98
	Reliability (%)	99.73	99.88	0.15

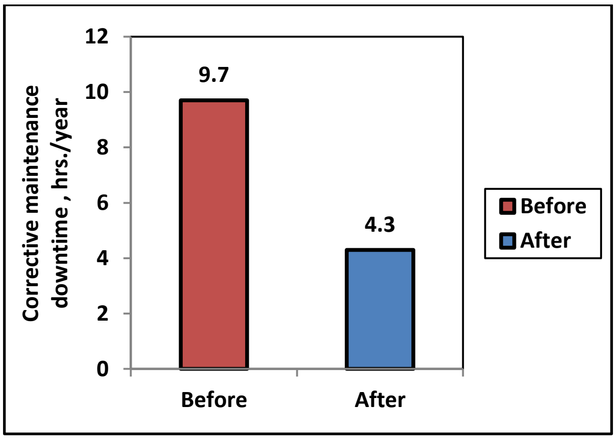


Figure 8. Corrective maintenance downtime for system

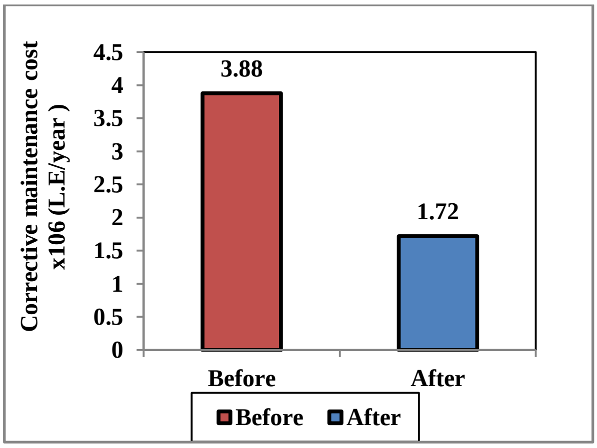


Figure 9. Corrective maintenance cost for system

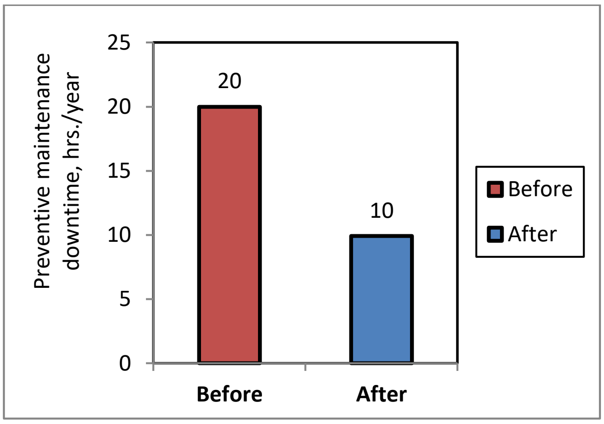


Figure 10. Preventive maintenance downtime for system

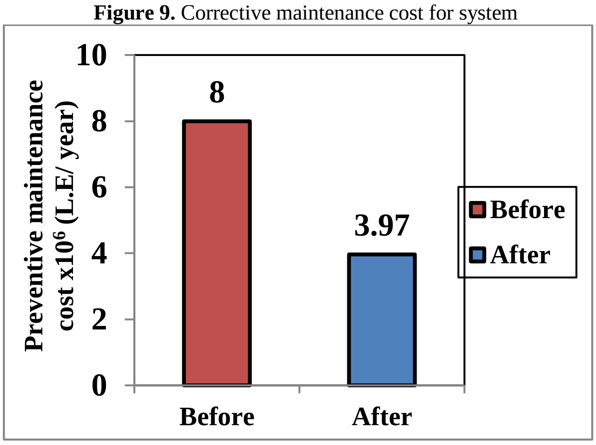


Figure 11. Preventive maintenance cost for system

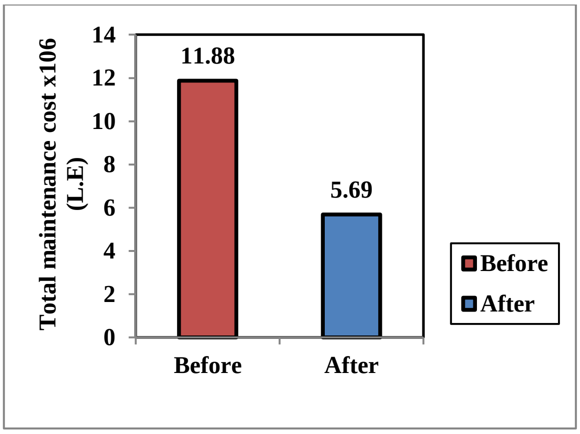


Figure 12. Total maintenance cost for system

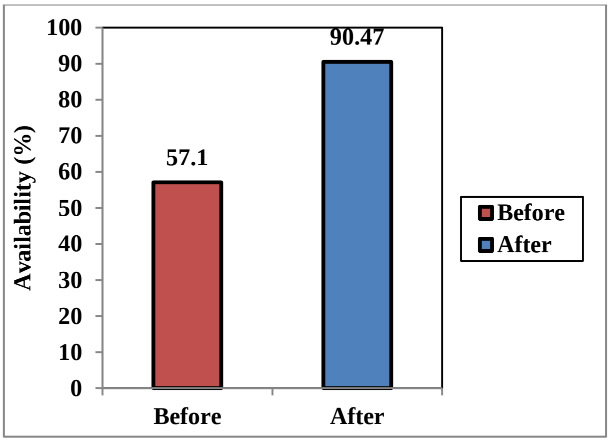


Figure 13. The availability analysis for system

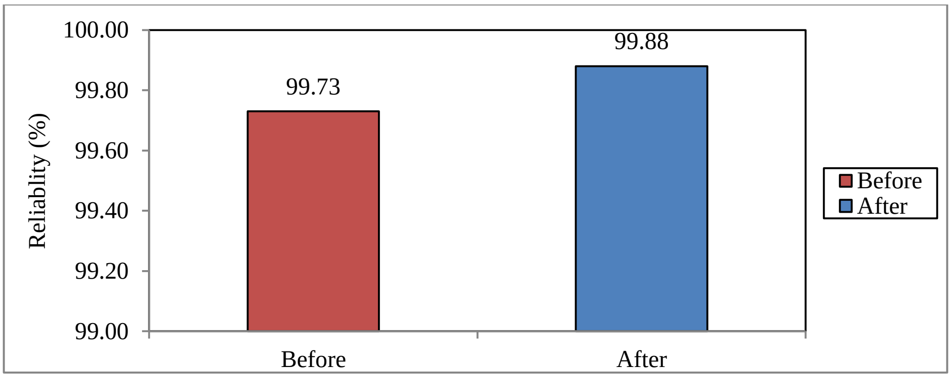


Figure 14. The reliability analysis for system

A comparison between the proposed RCM framework and other methods are introduced in table 12. The other methods include simple mode RCM [20], rational RCM [29], classical RCM [30], and group maintenance method [31]. Each of those methods has been validated in a different application, e.g., power distribution systems, manufacturing plant and CNC machine. The comparison between the proposed RCM framework and those methods is based on downtime reduction (%), reliability, availability (%), and maintenance cost reduction (%). We conduct the comparison with the available published results in their respective studies where not all measures are reported in those studies. The comparison indicates that the other methods succeeded to reduce the downtime between 33.15% and 38% while the proposed RCM framework realized a downtime reduction of 55.77%. The other methods succeeded to achieve a reliability that ranges between 87.2% and 92.1 while the proposed RCM framework improved the reliability to 99.88%. The maintenance cost reduction has also improved by 34.5% under the previous methods while the proposed RCM framework reduced the maintenance cost by 52.17%. As such, this comparison implies that the proposed RCM framework outperforms the other existing methods.

Table12. A comparison between the proposed RCM framework and relevant methods

No	Item	Relevant Methods				Proposed Framework RCM in present work
		RCM simple mode approach [20]	Rational RCM (RRCM) approach [29]	Classic RCM [30]	Group maintenance method [31]	
1	Application	-	Power distribution systems	Manufacturing plant in Poland	CNC Machine	Sugar Works Company in Egypt
2	Reduction downtime, %	Average 33.15		38	-	55.77
3	Reliability, %	-	87.2	-	Max. 92.1	99.88
4	Availability ,%	-	Mean availability 84	-	-	90.47
5	Reduced maintenance cost,%	-	34.5	-	-	52.17

9. Conclusions

A novel framework of RCM has been proposed and applied to a sugar–end plant in Fayoum Sugar Works Company. The new finding of this work shows that corrective maintenance downtime decreased from 9.7 hours/year to 4.3 hours/year and its cost decreased from 3.88×10^6 L.E/year to 1.72×10^6 L.E/year. In addition, preventive maintenance downtime decreased from 20 hours/year to 10 hours/year and its cost decreased from 8×10^6 L.E./year to 3.97×10^6 L.E./year. This means that proposed RCM saved 6.19×10^6 L.E in total maintenance cost. System availability and reliability are improved as well. Availability increased from 57.1% to 90.74% and reliability increased from 99.73% to 99.88%. New points of research can be investigated in future through various directions, e.g. the integration of the proposed methodology with other maintenance techniques, the proposed policy can be applied to other large industrial processes.

10. Acknowledgment

The authors would like to express the sincere appreciation for the staff members of the Fayoum Sugar Works Company, Kasr El Basel, Itsa, El Fayoum, Egypt, for their support during carrying out this work.

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