Impact of Reliability Centered Maintenance on Equipment Availability and Cost Optimization

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Abstract— **This paper aims to clarify the importance of applying the Reliability Centered Maintenance (RCM) methodology on critical systems. RCM is a well-established method in determining and optimizing the preventive maintenance strategies of equipment. The paper shows the importance of having reliable systems in the plant through addressing some case studies, where the number of maintenance orders before and after the implementation of RCM has been remarkably reduced. The associated costs and equipment availability were also observed. The economic benefits out of implementing RCM, the impact of applying RCM, and cost optimization were also demonstrated by presenting four case studies. Appling such reliability tool (RCM) on the critical systems of the plants will enable the organization to ensure the reliability and availability of the equipment in order to achieve the annual production target.**

Index Terms— **Reliability centered maintenance, Maintenance cost, System availability, Failure mode, Maintenance strategy.**

I. Introduction

PLANING of preventive maintenance (PM) of technical systems is a challenging task. A balance has to be made between the frequency and extension of the maintenance, and costs. The preventive maintenance is introduced to avoid the occurrence of failures of the system and reduce potential consequences of failures, but maintenance could in some cases also introduce failures. Both of these counteracting aspects are of relevance to preventive maintenance planning. Different tools have been developed to support the planning of PM and this paper addresses the Reliability Centered Maintenance (RCM) methodology. The main objective of RCM is to reduce maintenance costs and at the same time increase reliability and safety [1, 2].

The research objective is to study and analyzed the performance of the critical systems in one organization before implementing the RCM methodology. Then, the effect on the performance of these critical systems would be evaluated. Four case studies are presented. The first two cases discuss the relationship between implementation of RCM and the reduction of maintenance orders. The third case study demonstrates the reduction of maintenance cost, and the fourth case study demonstrates the increase in equipment availability with the implementation of RCM strategy.

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II. Literature Review

A. What is RCM

RCM is a systematic approach for identifying effective and efficient preventive maintenance tasks for items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks. Effective maintenance helps to increase revenues by increasing equipment performance and plant capacity, which will in turn maximize the volume of sales.

RCM is a structured process to determine the equipment maintenance strategies required for any physical asset to ensure it continues to fulfill its intended functions in its present operating context. Therefore, the goal of RCM is to determine the critically equipment in any process, and based on this information, design a customized preventive/predictive maintenance strategy for the organization. RCM initiatives, however, involve a tremendous amount of resources, time, and energy. Thus the process is an extremely time consuming and expensive too especially when done according to the textbook [3, 4, and 5].

Table 1: Maintenance Development [6]

Maintenance Strategy	Maintenance Approach	Signification
Breaking Maintenance	Fix it when broke	Large maintenance budget
Preventive Maintenance	Schedule Maintenance	Periodic component replacement
Predictive maintenance	Condition-based Monitoring	Maintenance decision based on equipment condition
Proactive maintenance	Detection of source of failures	Monitoring and correcting failing root causes

Table 1 shows how the maintenance strategies developed. Initially, maintenance was only to repair the equipment once it failed. Then, in addition to the corrective maintenance, scheduled (preventive) maintenance has been introduced. After that, the predictive maintenance approach has been introduced which depend on the equipment condition. Finally, the RCM approach has been introduced. RCM does not contain any new principles for performing maintenance; it is a more structured way of using the best methods and disciplines. RCM governs the maintenance policy at the level of plant or equipment type. The strength of RCM is that it produces extraordinarily robust and effective planned

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maintenance programs, even in situations where the development team have access to little or no historical data. If RCM is correctly applied, it can reduce the amount of routine maintenance work by a significant margin.

A proper implementation of RCM can lead to greater safety, improved operating performance, improved cost-effectiveness of maintenance, longer useful life of expensive items, a comprehensive database, greater motivation of individuals, better team work.

B. *Criticality assessment*

Criticality analysis is an important tool that provides valuable information for decisions about work priority, justifying resources to develop reliability strategies. Instead of hoping asset availability and reliability will improve by spending money and time on them, use criticality analysis to ensure resources are being spent in the most efficient way [1, 3, and 7]. In industrial plants, including the sudden failure of critical equipment can lead excessive loss in production output. Hence it will be most economical to predict the failure period of the critical equipment so as to proactively plan and schedule maintenance activities [8].

Plant, usually, composed of many types of equipment. Combination of equipment together forms a system. The systems in the plant have different level of importance. So, it is very important to decide which system to conduct the RCM study on. Deciding which system to study depends on different factors that will identify the criticality of each system. Usually, in a well-developed plant there is a clear guideline to define the criticality of the systems using the risk matrix guidelines. A Risk Matrix is a matrix that is used during Risk Assessment to define the various levels of risk as the product of the harm probability categories and harm severity categories. This is a simple mechanism to increase visibility of risks and assist management decision-making [9]. The following are the elements of a risk matrix.

- Consequence Categories: There are five consequences categories that can be used to assess the impact of a risk. 1) Financial, 2) Reputation 3) Operational or Production Loss 4) Health & Safety, and 5) Environmental

- Likelihood Scale: The type of scale to be used usually depends on the type of risk being frequency. Figure 2 shows the likelihood scale as L1, L2, L3, L4, and L5

- Consequence and Likelihood Scoring: The scores of consequence describe the increase in severity of the consequence (C1 to C5) with each level. Similarly the scores of the Likelihood describe the increase in the probability of likelihood (L) with each level.

III. Data Collection

Throughout this study, SAP system was used in order to collect all the related data required to perform the study. The numbers of different work orders raised against different systems and the associated cost is important part of the gathered data. That because the main focus in this study is to find the impact of applying the RCM on those systems in terms of the number of corrective maintenance order (M1), number of breakdown maintenance order (M2) and number of preventive maintenance order (M3). Also, the associated cost with each of the raised order whether it is increased or decreased.

In order to perform the RCM analysis, the following seven basic questions need to be answered by the RCM team [1, 10]:

1) What are the functions and desired performance of the (asset/system) in its present operating context (Functions)? 2) In what ways can it fail to fulfill its functions (Functional Failures)? 3) What causes each functional failure (Failure Modes)? 4) What happens when each failure occurs (Failure Effect)? 5) In what way does each failure matter (Failure Consequences)? 6) What should be done to predict or prevent each failure (Recommendations)? 7) What should be done if a suitable RCM task cannot be found (Default Actions)?

Example of RCM recommendations:

- Having stand by equipment
- Calibration
- Condition monitoring
- Increase maintenance frequency

The first step in accomplishing the RCM study is the identification of the critical equipment. A team of technical staff assigned to carry out Criticality Assessment. This team will consist of experience people in operation, process, maintenance mechanical, electrical and instruments, and external specialist if needed. Some specialist may be invited based on need such as Rotating specialist, inspection specialist, Sr. Reliability Engineer etc. Team will start the criticality assessment on system-by-system and equipment-by-equipment. Then, team will evaluate each system for the two dimensions of risk matrix (consequence and likelihood). It is very important to know that system consist of number of equipment and the criticality assessment will be done on the system as whole including the related equipment. It is preferable that RCM study to be conducted for all the equipment in the plant regardless of their criticality. As seen before, however, there are number of equipment in the plant that has a great impact once it fail. So, it is wise and logical to spend much of the time and effort on these critical systems or equipment and propose the suitable maintenance plan rather than spending much of time and effort in less critical equipment, which will gain very less of benefit. Number of systems with risk level 1 (RL1) and risk level 2 (RL2) are selected in the following case studies to demonstrate the effectiveness of applying RCM analysis, as they are the most critical failure type.

The measured Risk (Likelihood X Consequence) score should be fit in any one of the risk level ranges shown in Table 2. Table 3 shows example for Risk Matrix along with the Risk Levels that can be used to help in doing the criticality assessment

Table 2: Consequence and Likelihood Scoring

Consequence	Score	Likelihood	Score
C1 (Very High)	12	L1 (Very Likely)	8
C2 (High)	6	L2 (Likely)	6
C3 (Moderate)	4	L3 (Possible)	4
C4 (Low)	2	L4 (Unlikely)	2
C5 (Very Low)	1	L5 (Very Unlikely)	1

Table 3: Example for Risk Level in Matrix

Measured Risk Score (Likelihood X Consequence)	Risk Level
32 – 96	RL 1 (Major)
12 - 24	RL 2 (Significant)
6 – 8	RL 3 (Minor)
1 - 4	RL 4 (Insignificant)

IV. Case Studies

The number of different maintenance orders (M1): corrective maintenance orders, (M2): breakdown maintenance orders and (M3): planned maintenance orders were analyzed. In addition, the associated costs of the different maintenance orders were analyzed. In general, after implementing RCM recommendations, the number of corrective maintenance orders (M1) and the number of breakdown maintenance orders (M2) are reduced. In the other hand, the number of the planned maintenance orders (M3) increase. The reduction in M1 and M2 orders will have a great impact in optimizing the cost and the generation of M3 orders help in reducing the failures, safe the environment, keep the production continues and sustain the organization reputation. Also, that will help in improving the equipment availability. Four case studies of implementing RCM are presented below.

A. Case study No. 1: RCM and reduction of maintenance orders for Oxygen Supply System

This case study demonstrates the relationship of RCM implementation and the reduction in maintenance requests for oxygen supply system. The daily production of this plant is 650 metric tons, which is equivalent to 2.1 million SAR (one US Dollar = 3.75 SAR) per day. The function of this system is to supply oxygen to Oxygen Mixer System (OMS) continuously for safe mixing of O2 in cycle gas. One of the major equipment covered by this system is a relive valve. If the relive valve opens, this will cause the OMS to shut down which will lead to shut down the complete plant. This system has RL1 with total risk score of 77.

Table 4 shows the number of maintenance orders performed on this system from the year 2007 till the year 2015 associated with the costs of those maintenance orders. Figure 1 shows the trend of the three maintenance orders done on this system before and after the RCM study on 2012.

Table 4: Data for Oxygen Supply System

Year	M1 Count	M2 Count	M3 Count	M1 Cost	M2 Cost	M3 Cost
2007	4	0	0	3,376.33	0	0
2008	8	0	15	18,769.15	0	25,071.88
2009	3	0	5	8,133.05	0	10,074.10
2010	1	0	10	1,267.04	0	16,419.56
2011	0	0	10	0	0	21,251.10
2012	2	0	13	5,969.80	0	30,613.31
2013	1	0	16	673.54	0	36,791.94
2014	4	0	19	6,889.46	0	37,940.52
2015	4	0	16	15,550.34	0	39,288.54

It is very clear that the number of corrective maintenance (M1) is decreasing with time, which will increase the availability of the system as required. On the other hand, the number of preventive maintenance (M3) increased with time, which is a result of the RCM implementation. For the breakdown maintenance order (M2), no breakdown has been reported for this system since 2007. Although the number of M1 orders decreased with time but a slight increase has been observed since 2011. Corrective maintenance cannot be eliminated totally. In this particular case, the increase in the number of M1 orders is due to implementing one of the RCM recommendations, which is “run to fail strategy”. Such maintenance order will not be registered as M3 order because the date of the failure is not known and there was mitigation at the time of failure. Because it is not planned order, it cannot be registered as M3. In general, the trend of M1 orders is slopping downward whereas the M3 orders trend is slopping upward.

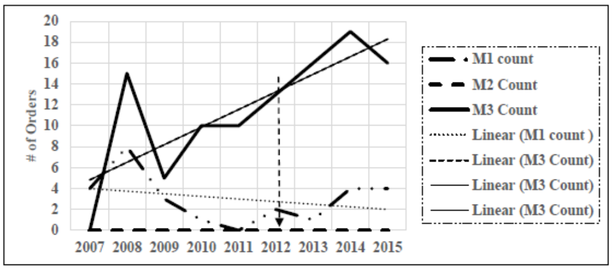

Figure 1: Number of Maintenance orders before & after RCM for Oxygen Supply System

Figure 2 shows the cost related to these maintenance orders. It is very clear that the cost associated with the corrective maintenance orders (M1) is decreasing with time because the number of the M1 orders has been decreased. As stated before, the associated cost started to increase after 2011, which is due to performing the M1 order of “run to fail strategy”.

Such increase in cost is justified for the organization management. However, the associated cost with preventive maintenance orders is increasing with time because there are more M3 orders generated out of the RCM. This increase in the cost of M3 orders is well justified, as this cost will have a direct impact on increasing the system life and availability as required. No cost has been encountered for M2 orders, as there is no M2 orders happened.

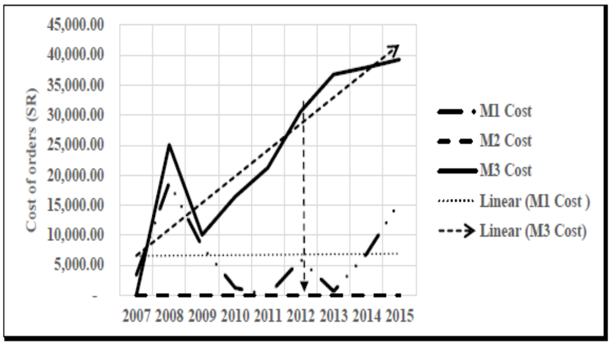

Figure 2: Cost of Maintenance Order before & after RCM for Oxygen Supply System

In general, the cost for the M1 orders is almost steady throughout the years whereas the cost associated with M3 orders is increasing with the years as seen by the trend line.

B. Case study No. 2: RCM and reduction of Maintenance orders for Neutralization system

This system is used in Utility and Offsite plant. This plant is responsible to feed the other production plants with the utilities required for their production (cooling water, sea water, nitrogen, oxygen, steam…). The criticality assessment for this system is RL 2 with total risk score of 57. Table 5 shows the maintenance data related to this system.

Table 5: Data for Demineralized Neutralization system

Year	M1 Count	M2 Count	M3 Count	M1 Cost	M2 Cost	M3 Cost
2007	25	0	28	29,720.11	0	12,312.53
2008	8	0	4	8,437.85	0	5,447.55
2009	26	0	1	19,796.42	0	2,925.17
2010	33	0	8	41,048.25	0	9,994.38
2011	25	1	29	73,422.50	4,487.33	38,016.13
2012	11	0	29	39,679.59	0	43,027.33
2013	7	0	30	13,398.28	0	40,622.53
2014	4	1	53	9,775.06	9,726.00	65,451.81
2015	5	0	61	11,179.12	0	67,231.09

The RCM study implemented for this system in 2012 as highlighted in the table. Figure 3 shows the number of maintenance ordered performed on this system starting from 2007 till 2015.

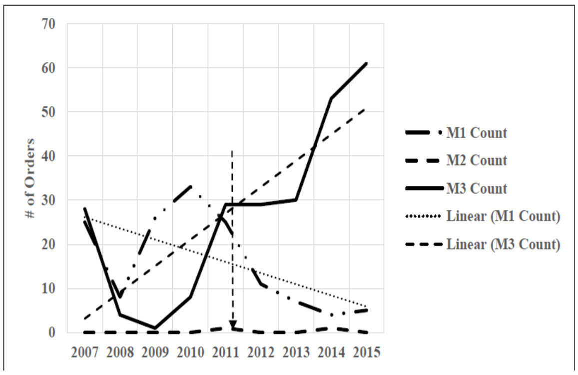

Figure 3: Number of Maintenance Order before & after RCM

It can be observed that the number of the corrective maintenance orders (M1) is decreasing with time especially after the implementation of RCM study on 2011.

It is clearly shown that the number of preventive maintenance orders (M3) is having an increasing trend over the years. Figure 4 shows the trend of the cost along the years. The reduction in the cost of the corrective maintenance orders (M1) is clear, which means that the equipment availability is in a good condition. Also, the increasing trend of the preventive maintenance orders (M3) cost is well justified as that related to the decrease in the number of M1 orders and an increase in M3 orders.

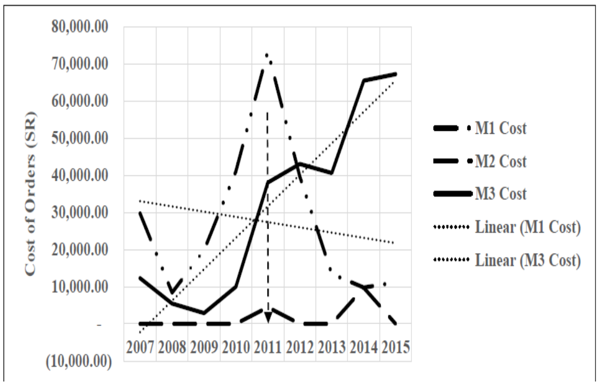

Figure 4: Cost of Maintenance Order before & after RCM

C. Case study No. 3: RCM and maintenance cost

This case study demonstrates the potential saving generated from applying the RCM. Table 6 shows the potential economic benefits of applying RCM in 5 plants. The number of systems covered by RCM study is different from plant to plant.

The first column, “Economic Risk before RCM” represents the risk of these systems if it fails as cost wise according to risk matrix. The systems are with risk level 1 (RL1: major) and risk level 2 (RL2: significant). After implementing the recommendations of RCM study, which might be (choosing the appropriate maintenance strategy, introducing PM, increasing PM, change frequency of PM, do regular inspection) it is important to see how much does these recommendations contribute to the economic risk.

Table 6: RCM Potential Economic Benefits

Plant	Economic Risk before RCM	Economic Risk after RCM	Potential Economic benefit	No. of Systems
Plant 1	295,436,668.45	53,827,613.09	177,004,708.95	23
Plant 2	233,828,669.05	42,664,530.12	153,940,510.24	18
Plant 3	213,862,894.20	28,737,394.40	116,618,562.46	26
Plant 4	1,036,494,452.25	353,492,785.59	622,056,581.70	15
Plant 5	33,794,656.15	5,678,651.15	20,051,757.31	62
Total	1,813,417,340.10	484,400,974.34	1,089,672,120.65	144

That is appeared in the “Economic Risk after RCM” column, which means if the proposed recommendations have been implemented; the risk associated with this system

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will be reduced to the noted value. Then, the percentage of reduction in the economic risk due to implementing RCM study on these specific systems is seen. It is observed that there is a remarkable reduction in all the plants. Figure 5 shows the potential economic benefits of implementing the RCM recommendations for different plants. Although the number of systems is varying from plant to plant but the associated potential economic benefits of RCM is not depending on how many systems covered by the RCM as shown in Table 6.

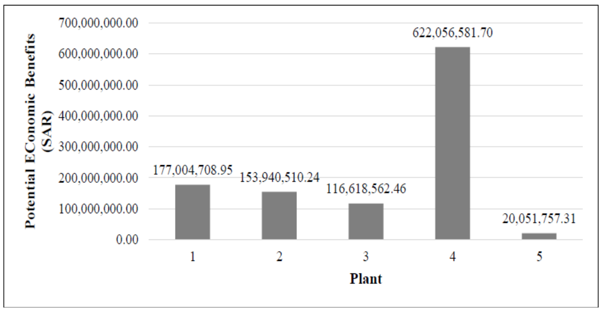

Figure 5: RCM Potential Economic benefit (SAR) vs. Plants

In general, this reduction can be also translated as a shift in moving the risk level of these systems from the risk level 1 (RL1: major) and risk level 2 (RL2: significant) to lower risk levels (RL3: minor or RL4: insignificant).

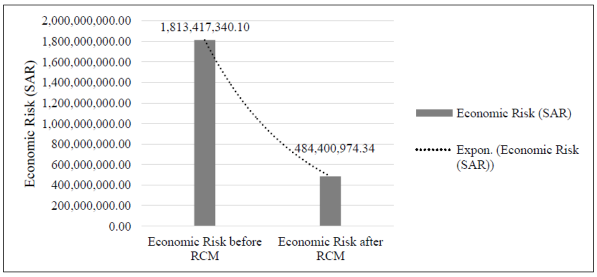

Figure 6: Economic Risk (SAR) before and after RCM

Figure 6 shows the amount of reduction in the economic risk due to the implementation of the RCM recommendations by year 2015. This will result in saving the maintenance cost, improving the equipment's reliability and elimination of the unwanted preventive maintenance. The potential economic benefits of RCM will include the followings: a) reduced production losses and maintenance cost (Economic Benefit) b) Increased reliability and up time of an asset c) reduced failure consequences d) improved mechanical integrity, and e) Improved product quality

It is important to assess whether the generated RCM recommendations have improve the equipment behavior or reduce the amount of maintenance orders in the plants, which can be translated as the maintenance cost. Table 7 shows a case study conducted in one organization where the total maintenance cost has been collected from five different plants along with the cost of the RCM recommendations.

Figure 7 shows both the total maintenance cost and the cost of the RCM recommendations. It is clearly seen that the cost of implementing the RCM recommendations has an increasing trend with the years. That will indicate that out of the total maintenance cost, RCM work orders have a quit good percentage of cost directed to the planned maintenance rather than the corrective maintenance and the breakdown maintenance. It also observed that the percentage of the RCM cost contribution to the total maintenance cost that the percentage of RCM recommendation cost is increasing year-after-year

Table 7: Total Maintenance cost to RCM recommendation Cost

Year	Total Maintenance Cost	RCM Recommendations Cost	% of RCM Cost Contribution
2007	36,826,886.67	5,949,947.4	16.16%
2008	41,383,500.86	6,480,760.76	15.66%
2009	23,950,297.61	7,630,105.94	31.86%
2010	39,517,968.07	12,505,842.33	31.65%
2011	33,396,948.24	14,939,322.88	44.73%
2012	37,826,446.56	15,334,293.74	40.54%
2013	42,842,600.51	18,618,842.85	43.46%
2014	43,401,531.99	19,348,677.75	44.58%
2015	33,019,342.67	16,077,540.67	48.69%
TOTAL	**332,165,523.2**	**116,885,334.3**	**35.19%**

The increase in the RCM recommendations cost compare to the total maintenance cost indicates the effectiveness of those recommendations in lowering the corrective maintenance orders (M1) and the breakdown maintenance orders (M2) and directing the resources to implement the RCM recommendations.

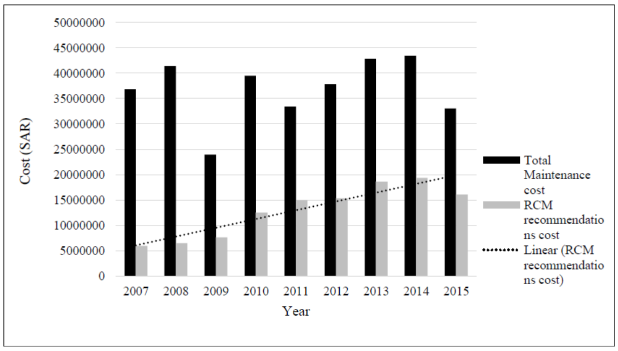

Figure 7: Total Maintenance cost to RCM recommendation Cost

These systems need some time to become more mature and the benefits will be realized more clearly. If the same manner of applying the RCM continues, the total maintenance cost will decrease and the cost of the RCM recommendations will increase with time.

D. Case study No. 4: RCM and equipment availability

This case study shows the improvement in the equipment availability that is considered as a very important measure to the effectiveness of implementing the RCM recommendations. Availability is the time that a piece of equipment or system is capable of performing its intended functions divided by total time. It is usually expressed as a percentage. Table 8 shows the equipment availability data between years 2007 and 2014. The sum of the equipment's downtime in hours and the total of equipment availability in hours are shown. By applying the equipment availability concept, the equipment availability is shown in percentage.

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The downtime of the equipment cannot be eliminated 100% but it can be reduced significantly by implementing some of the RCM recommendations. By having standby equipment that will help in the event of equipment failure, and the other one will take over, which will reduce the downtime of the equipment in total and result in continuing the operation with minimum interruption.

Table 8: Equipment Availability

Year	Sum of Downtime (Hours)	Sum of Equipment Availability Time (Hours)	Equipment Availability
2007	776.99	233,833,800	100.00%
2008	1751.16	321,025,512	100.00%
2009	10693.16	409,031,184	100.00%
2010	13668.04	505,272,840	100.00%
2011	13897.4	602,684,952	100.00%
2012	14565.03	706,952,064	100.00%
2013	17552.56	809,871,768	100.00%
2014	17843.91	1,167,750,672	100.00%

Also, the right implementation of the RCM recommendations will increase the equipment reliability and that helps in improving the equipment availability.

It is clearly observed that the equipment availability between years 2007 till 2014 has an increasing trend. Figure 8 shows the equipment availability trend through the years having a continuous improvement, which will have a positive impact on the equipment to perform its intended function as required without any interruption. Ultimately, this will be a good support to have continues production of the plant. Keep up the equipment available as required is one of the main objectives of the implementing the RCM recommendations.

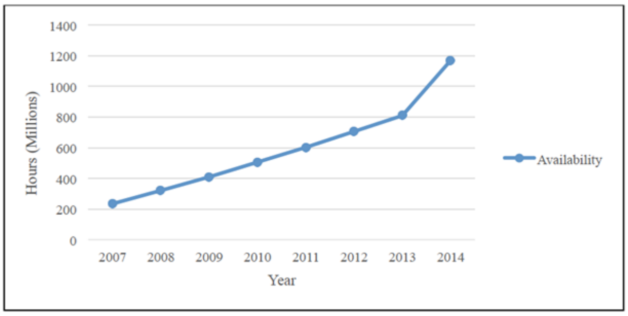

Figure 8: Equipment Availability

V. Conclusion

As demonstrated in the case studies, there is a good reduction in the number of the corrective maintenance orders (M1). A reduction in the number of corrective maintenance orders (M1) implies that plant experienced less number of failures, which will result in increasing the equipment availability of that system. As a result of the reduction in the number of M1 orders, the associated cost reduced, which gives a clear indication about the impact of applying the RCM in reducing the maintenance cost. It also appears that the number of preventive maintenance orders (M3) has increase for some of the systems after implementing the RCM recommendations. That means the RCM team has recommended doing some of preventive maintenance order (inspection, overhaul, calibration…), which will help in avoiding the failures, discovered during the FMECA. The associated cost with M3 orders is justified cost as that cost will be reflected on the improvement of equipment condition and service life and eventually in the reliability of the plant. The most important aspect is to eliminate the number of breakdown maintenance orders (M2). That is because whenever there is M2 order means plant is under shutdown, which is usually not preferred and not acceptable by the plant management especially if it is due to not implementing the reliability recommendations. Although the cost associated with M2 orders appears to be very low or even negligible, however, that cost is only for repairing the failed equipment and not representing the total cost due to M2 orders, which lead to shut down the complete plant. RCM will develop recommendations and along with these recommendations, time of the implementation. Usually the time for implementing those recommendations will be coupled with planned shutdown of the plant. So, no process production will be affected and known frequency for doing the maintenance is already identified. One should not think that by implementing the RCM recommendations the risk would be completely eliminated. RCM will help in reducing the risk associated with these systems. The effect of implementing the RCM recommendations has been observed on the number of the maintenance orders (corrective, breakdown and preventive) and the cost associated with it. Also, the risk level of the critical systems has been declined after implementing the suggested RCM recommendations. Plant managements need to implement the RCM methodology on the critical systems as early as possible in order to decide and optimize the preventive maintenance strategies.

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