The Reliability-Centered Maintenance (RCM) effect on plant availability and downtime loss in the process industry

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Abstract. The process industry needs an optimal preventive maintenance strategy because the even breakdown of one machine can cause an unexpected shutdown for the whole production process. The case study company (CSC), one of the fertilizer companies in Indonesia implements Reliability-centered Maintenance (RCM) as their preventive maintenance strategy to decrease downtime and increase the availability of the production plants. Eversince the RCM implementation started in 2007, there is no study to evaluate the RCM implementation. Relations between the two parameters (downtime loss and availability) are analyzed using the Pearson correlation test as a statistical method to evaluate the RCM implementation. The results of the analysis show that the R-value of downtime loss and availability of K-3 Ammonia and Urea plants are increased, while the R-value of K-4 Ammonia and Urea Plants are decreased. The RCM implemented in K-4 plants should be evaluated respectively, because the decreasing of the correlation means the RCM implementation on the plant still has not met its propose and there are still hidden factors that affect the availability and downtime loss of the plant, regardless the RCM implementation.

1. Introduction

In this era of the ever-growing industry, companies compete in giving satisfaction to the consumer to meet the needs demanded by consumers. To maintain company productivity, the high availability of industrial facilities is required. One of the major facilities that strongly supports the productivity of a company is the condition of the equipment or machine. Damage (breakdown) on one machine can cause unexpected shutdowns for the whole process in continuous production, such as the process industry [1]. In these conditions, a series of an optimal preventive maintenance strategy is required on the machine because it is well-known that maintenance, production, and quality are strongly linked to each other [2].

Effective maintenance is critical to many operations. It extends equipment life, improves equipment availability and retains equipment in proper condition. Conversely, poorly maintained equipment may lead to more frequent equipment failures, poor utilization of equipment and delayed production schedules [3]. Maintenance is defined as the combination of all technical and administrative actions, including supervision, which ensures that a system is in its required functioning state [4]. A well-implemented integrated asset management and maintenance system can impact every section of an organization, increasing asset uptimes, reducing maintenance costs, increasing benefits, and enhancing the reputation of the business with its customers [5].

A lot of maintenance strategies have been developed during the last few years. RCM has been one of the most recent strategies in maintenance around the world. Originally, RCM is defined as a systematic process for development and optimization of the maintenance requirements of a physical resource in its operating context to realize its inherent reliability by logically incorporating the maintenance strategies like reactive, preventive, condition-based and proactive maintenance. Around the world, it is an imperative technology in the industrial maintenance field that can be functional to improve the equipment availability and reliability and reduce operational and maintenance costs. The
theory of RCM is the function of the operating system to recognize the consequences of the failure by the failure analysis and system function [6].

RCM implementation has to be evaluated by comparing the value of some variables before and after RCM has been applied as a measurement of the effectiveness of RCM implementation in the company. Nabhan (2010) stated that after the measurement of RCM effectiveness was carried out, some industries are not applying RCM effectively. Regarding Nabhan (2010) statement, the evaluation of the effectiveness of RCM implementation should be done.

In the previous researches, certain parameters are used to evaluate RCM. Unexpected failures rate, plant availability and maintenance cost are the typical global measurements of the RCM program constructed. Fore and Mudavanhu evaluate RCM using gaps in production output, total downtime, and availability and machine utilization. Despite total downtime, other related parameters should be considered are the mean time between failures (MTBF) and mean time to repair (MTTR) [5].

The case study company (CSC) has been implementing Reliability-Centered Maintenance (RCM) as its preventive maintenance strategy in the various plants. The company began to implement RCM in 2007, starting from K-3 urea & ammonia plant and K-4 urea & ammonia plant, and then spread to other plants. Earlier the company applying Root Cause Analysis (RCA) in the execution of its maintenance. Since its implementation in 2007, there is no study to evaluate the RCM implementation whether it meets its purpose to increase the availability and reliability of the plant or assets. The study analyzing the relation of downtime loss and availability of the plant after RCM is implemented then proposed as this study, to show the effect of RCM implementation on the availability and reliability of the plant and whether the purpose of RCM has met the expectation or not. Both parameters (availability and downtime loss) are used because high availability is one of the objectives of maintenance in the company. Despite the availability, downtime cost is another indicator highlighted in key literature [8]. In this study, downtime cost represented by downtime loss is one of the indicators used to determine the successful implementation of RCM. The purpose of this research is to analyze reliability-centered maintenance (RCM) practice relation with availability and downtime loss in CSC plants. The study is conducted on K-3 Urea and Ammonia plant, and K-4 Urea and Ammonia plant, because that plant has a level of the highest average production.

2. Research Methodology
As mentioned before, the analysis of RCM implementation is done by using the parameters of availability and downtime loss. Both parameters are analyzed using a statistical method. The statistical method used is the Pearson correlation. The Pearson correlation test has been conducted to understand the relationship between maintenance measurement factors [1]. Correlation tests performed on the availability and downtime loss value at the time before and after the implementation of RCM. Before performing the correlation and calculating the value of availability and downtime loss, we need to identify the amount of downtime that occurs in each plant. Downtime is used to calculate the value of availability and downtime loss. Definition of downtime, availability, downtime loss and correlation tests used are as follows:

2.1. Downtime
Downtime is a time when the machine/equipment is not in a condition to be able to perform its function. Downtime is calculated from when the machine does not function until the machine back in a position to function as it should, after repair. The downtime machine is idle or length of time in which the unit can no longer perform its function as expected. This occurs when a unit experiencing problems such as damage to the machine which can interfere with the performance of the machine as a whole including the quality of the product or its production speed so it takes a certain time to restore the function of these units in the original condition [9] [10].

Goyal and Nand (2012), in their research, covering 29 ammonia plants, stated that downtime in ammonia plants is due to plant-related and external problems. The plant-related problems consist of problems due to mechanical, electrical, instrumentation, process and miscellaneous failures of plant and
equipment. The external problems cause downtime such as shortage of raw materials, failure of external power, shortage of water and labour problems [11].

2.2. Availability
Availability is a ratio that illustrates the use of the time available for the operations of machinery and equipment. The availability rate is influenced by two components, namely equipment failure and setup and adjustment losses. The availability is the ratio of the operation time, by eliminating unplanned downtime of equipment to the loading time. Operation time is a time of plant operation include the total downtime. While the loading time is the only time plant operation does not include planned downtime. The formulations used are as follows [12]:

\[
\begin{align*}
\text{Loading Time} &= \text{Base Production Time} - \text{Planned Downtime} \\
\text{Operation Time} &= \text{Loading Time} - \text{Unplanned Downtime} \\
\text{Availability} &= \frac{\text{Operation Time}}{\text{Loading Time}} \times 100\%
\end{align*}
\]

2.3. Downtime Loss
Khasanah (2015) state that the downtime loss is the loss of production caused by the downtime. Maintenance-related downtime is the biggest contributor to low production performance [14]. Total downtime comprised of unplanned downtime and planned downtime. Downtime can be defined in a loss of money, the amount of production (tonnes), or time. Variables used to calculate are the actual production (AP), operating time and total downtime. The formula is as follows:

\[
\text{Downtime Loss} = \text{Total Downtime} \times \text{Actual Production Rate}
\]

2.4. Correlation Test (Pearson Correlation)
Correlation is a statistical term that states the degree of a linear relationship (unidirectional not reciprocal) between two or more variables, which was discovered by Karl Pearson at the beginning of 1900. Therefore, known as the Pearson Correlation Product Moment (PPM). Correlation is a statistical analysis technique most used by researchers. The magnitude of the correlation numbers is called the correlation coefficient is expressed by the symbol (R). Formulations for R as follows [15].

\[
R_{xy} = \frac{n \sum XY - (\sum X)(\sum Y)}{\sqrt{[n \sum X^2 - (\sum X)^2] [n \sum Y^2 - (\sum Y)^2]}}
\]

The R-value generated is not more than 1 and less than -1 (-1 \( < r < 1 \)). The resulting R-values can show the correlation pattern between variables used (x and y). The correlation patterns among others walking the same direction if the R-value is positive (+), running in the opposite direction if the R-value is negative (-), and not correlated if R-value = 0. The coefficient R if close to 1 / -1 then increasingly strong correlation exists, otherwise if closer to 0, then the correlation is lower. The size of the correlation can be observed interpretation in Table 1 [15] [16].

Based on the theory, the relation of availability and downtime loss should increase after the implementation of RCM. That is, R-value after implementation of RCM will be higher than before the implementation of RCM. Because after implementation of RCM the plant could prevent breakdown and unexpected shutdown.
2.5. **Mathematic Relation between Availability and Downtime Loss**

A mathematical relation of availability and downtime loss is performed by using the substitution of equations (3) and (5). The comparison is done as follows [12]:

Based on the equation (3), then

\[
\text{Operation Time (OT)} = \text{Availability} \times \text{Loading Time (LT)}
\]

Based on the equation (5), then

\[
\text{Downtime Loss} = \frac{\text{Downtime}}{\text{Operation Time (OT)}}\times \text{Actual Production (AP)}
\]

Substitute equation (7) and (8), then

\[
\text{Downtime Loss} = \frac{1}{\text{Availability} \times \text{Loading Time}} \times \text{Actual Production (AP)} \times \text{Downtime}
\]

Based on the equation (10), it is known that the downtime loss (DL) is inversely proportional to the value of availability, which means the value of downtime loss and availability will run in the opposite direction. That is, if downtime loss is little, then availability value is high, and vice versa.

2.6. **Data Collection**

2.6.1. **Location and Time Research.** The study was conducted at the factory K-3 and K-4 plant of ammonia and urea in CSC. The data used in this research is secondary data of the company that started in 2001 to 2018.

2.6.2. **Data Collection and Processing Methods.** Data needed in this research is secondary data of companies that include data on the amount of production, production time data, and the data of downtime occurrence. Other tasks include supporting data relating to research as previous research literature, and theoretical foundations derived from books and journals. Then the data processing is done to calculate the value of availability and downtime loss using the formula equation above. Then, test the correlation between the availability and downtime loss at the time before and after the implementation of RCM to determine differences RCM relationship after implementing at the plant. A correlation test was done manually using the above formula equation and performed using the software as a tool.

3. **Data Result, Analysis and Discussion**

3.1. **Data on Loading Time and Operation Time**

Data on loading time and operation time found using equation (1) and (2). Loading time found by using data of base production time and planned downtime. While operation time found by using data of loading time and unplanned downtime. The data of loading time four plants as the following Table 2.
Table 2. Data on loading time and operation time.

| RCM Implementation | Year | Ammonia K-3 | Urea K-3 | Ammonia K-4 | Urea K-4 | Ammonia K-3 | Urea K-3 | Ammonia K-4 | Urea K-4 |
|--------------------|------|--------------|----------|--------------|----------|--------------|----------|--------------|----------|
| BEFORE RCM         | 2001 | 8160.00      | 8160.00  | -            | -        | 7120.80      | 6683.52  | -            | -        |
|                    | 2002 | 8760.00      | 8760.00  | 1200.00      | 8586.00  | 8457.60      | 8319.60  | 1164.00      | 2123.04  |
|                    | 2003 | 7786.32      | 7776.00  | 8760.00      | 8760.00  | 7663.68      | 7166.16  | 6417.36      | 6459.36  |
|                    | 2004 | 8784.00      | 8784.00  | 8418.96      | 8403.36  | 8387.76      | 8310.48  | 8108.40      | 6258.96  |
|                    | 2005 | 8786.00      | 8786.00  | 8456.16      | 8435.76  | 8760.00      | 8760.00  | 8308.56      | 7597.68  |
|                    | 2006 | 8256.00      | 8256.00  | 8760.00      | 8760.00  | 7648.80      | 7534.80  | 7408.08      | 6492.96  |
| AFTER RCM          | 2007 | 8760.00      | 8760.00  | 8424.00      | 8424.00  | 8565.84      | 8463.84  | 8075.28      | 7664.64  |
|                    | 2008 | 8373.60      | 8245.20  | 8784.00      | 8784.00  | 8145.36      | 7799.04  | 8685.36      | 8516.16  |
|                    | 2009 | 8760.00      | 8760.00  | 8376.00      | 8376.00  | 8752.56      | 8712.00  | 8193.12      | 8027.76  |
|                    | 2010 | 8269.20      | 8254.80  | 8760.00      | 8760.00  | 8109.84      | 8044.32  | 8541.36      | 8367.84  |
|                    | 2011 | 8784.00      | 8784.00  | 8348.64      | 8342.88  | 8717.04      | 8695.92  | 8234.40      | 8147.76  |
|                    | 2012 | 8784.00      | 8784.00  | 8348.64      | 8342.88  | 8717.04      | 8695.92  | 8234.40      | 8147.76  |
|                    | 2013 | 8507.28      | 8487.12  | 8760.00      | 8760.00  | 8377.47      | 8303.52  | 8668.80      | 8691.60  |
|                    | 2014 | 8760.00      | 8760.00  | 8760.00      | 8760.00  | 8611.20      | 8421.84  | 8866.56      | 8230.08  |
|                    | 2015 | 8256.00      | 8265.12  | 8760.00      | 8760.00  | 7592.64      | 7818.72  | 8725.20      | 8085.25  |
|                    | 2016 | 8784.00      | 8784.00  | 8223.84      | 8115.84  | 8590.08      | 8480.16  | 7816.08      | 7071.60  |
|                    | 2017 | 8256.00      | 8256.00  | 8760.00      | 8760.00  | 6979.92      | 6440.64  | 8650.08      | 8491.68  |
|                    | 2018 | 8760.00      | 8760.00  | 8211.12      | 8268.96  | 8731.20      | 8462.64  | 8211.12      | 8227.44  |

In 2001 the factory K-4 has not been put into operation so that loading time and operation time cannot be calculated. Based on Table 2, it is known that the implementation of RCM began in 2007 onward. The data from 2001 to 2006 represents the condition before RCM implemented on the plant. The highest to the lowest average of loading time and operation time is start from K-3 ammonia plant, K-3 urea plant, and K-4 ammonia plant in 18 years.

3.2. Data on Availability and Downtime Loss
The availability is calculated using equation (3). The downtime loss is calculated using equation (4) and (5). Downtime loss is found by using data of actual production, operation time, and total downtime. The availability and downtime loss value for each plant per year is shown in Table 3.

Table 3. Data of availability and downtime loss, before and after RCM implementation.

| RCM Implementation | Year | Ammonia | Urea | Availability (%) | Downtime Loss (ton) |
|--------------------|------|---------|------|------------------|---------------------|
|                    |      | K-3     | K-4  | K-3              | K-4                 |
| BEFORE RCM         | 2001 | 87.26   | 81.91| -                | -                   |
|                    | 2002 | 96.55   | 94.97| 97.00            | 36.25               |
|                    | 2003 | 98.42   | 92.16| 73.26            | 73.74               |
|                    | 2004 | 95.49   | 94.61| 96.31            | 74.48               |
|                    | 2005 | 100.00  | 99.00| 92.85            | 90.07               |
|                    | 2006 | 92.65   | 91.26| 84.57            | 74.12               |
| Mean               | 95.06| 92.49   | 89.88| 69.73            | 35593.6             |
| AFTER RCM          | 2007 | 97.78   | 96.62| 95.86            | 90.99               |
|                    | 2008 | 97.27   | 94.59| 98.88            | 96.95               |
|                    | 2009 | 99.92   | 99.45| 97.82            | 95.84               |
|                    | 2010 | 98.07   | 97.45| 97.50            | 95.52               |
|                    | 2011 | 100.00  | 98.93| 96.84            | 92.23               |
|                    | 2012 | 99.24   | 99.00| 98.63            | 97.66               |
|                    | 2013 | 98.47   | 97.84| 98.96            | 99.22               |
|                    | 2014 | 98.30   | 96.14| 98.96            | 93.95               |
|                    | 2015 | 91.97   | 94.60| 99.60            | 92.30               |
|                    | 2016 | 97.79   | 96.54| 95.04            | 87.13               |
|                    | 2017 | 84.54   | 78.01| 98.75            | 96.94               |
|                    | 2018 | 99.67   | 96.61| 100.00           | 99.50               |
| Mean               | 96.92| 95.48   | 98.07| 94.85            | 19363.0             |

42361.1 15182.9 42676.1
Correlation test is used to determine the correlation R-value between availability and downtime loss at the time before and after the implementation of RCM. The variables that used are the availability value as X and downtime loss as Y. The availability value is used as an independent variable of the correlation test because it is one of the purposes of maintenance, which ensures the optimum level of the facility. While downtime loss is used as the dependent variable of correlation test and as one of the parameters to determine the success of the RCM implementation. Downtime loss is also used to find out the amount of loss generated based on the availability value. This correlation test calculation using the SPSS software program. It can be seen the R-value that will demonstrate the significance of the correlation between availability and downtime loss. The correlation test was conducted with the two treatments, that are before the implementation of RCM in 2001-2006 and after implementation of RCM in 2007-2018. The correlation value and mean value of availability and downtime loss before and after the implementation of RCM are summarized in Table 4.

| Plant  | RCM Implementation | R-value comparison | Mean value comparison |
|--------|--------------------|--------------------|----------------------|
|        | Correlation value  | Correlation pattern| Availability (%)      | A Availability Mean | Downtime Loss (ton) | A Downtime Loss |
| Ammonia K-3 | Before RCM   | -0.7745   | Opposite direction   | Enough               | 95.06              | 1.86            | 33,593.6       | -14,230.6 |
|         | After RCM     | -0.9504   | Opposite direction   | High                 | 96.92              | 19,363.0        |                 |            |
| Urea K-3 | Before RCM   | -0.9188   | Opposite direction   | High                 | 92.49              | 3.00            | 68,947.4       | -26,586.4 |
|         | After RCM     | -0.9526   | Opposite direction   | High                 | 95.48              | 42,361.1        |                 |            |
| Ammonia K-4 | Before RCM   | -0.9514   | Opposite direction   | High                 | 89.88              | 8.19            | 39,628.6       | -24,445.8 |
|         | After RCM     | -0.6438   | Opposite direction   | Enough               | 98.07              | 15,182.9        |                 |            |
| Urea K-4 | Before RCM   | -0.9551   | Opposite direction   | High                 | 69.73              | 25.12           | 141,138.9      | -98,462.8 |
|         | After RCM     | -0.8383   | Opposite direction   | High                 | 94.85              | 25.12           | 42,676.1       |                 |

Even though the mean value of availability and downtime loss before and after RCM shows that the availability increase and downtime loss decrease after RCM has been implemented to the Ammonia and Urea plants, but the correlation shows that for some plant, the correlation decrease after RCM has implemented to the plant.

Based on the equation (10), it is known that the downtime loss (DL) is inversely proportional to the availability value, which means the value of downtime loss and availability will run in the opposite direction, that is, if downtime loss is little then availability value is high, and vice versa. While affecting the level of relations between the two parameters is Loading Time (LT), which means Planned Downtime at the mill is very influential on the level of relationship of downtime loss and availability. Then the actual production and total downtime can also affect the relationship of downtime loss and availability of the plant. In theoretical, the relation of availability and downtime loss will increase after the implementation of RCM. That is R-value correlation after implementation of RCM will be higher than before the implementation of RCM. Because after implementation of RCM the plant could prevent production failure. As in theory, the correlation value will increase if the relation of availability and downtime loss are inversely proportional (the value of availability increases, so the downtime loss decreases). So, comparing with the theory, it’s true that the relation of availability and downtime loss in the K-3 plant occurs in the opposite direction and will increase after the implementation of RCM. But, in the K-4 plant does not seem following the theory.

By analysing the correlation and the mean value of availability and downtime loss before and after RCM implementation, it shows that the implementation of RCM in the K-3 plant can improve the relationship between availability and downtime loss. It is proven that the high availability value can reduce the level of downtime loss, and the correlation of those two variables increases after RCM has
been implemented to the plant. Meanwhile, the implementation of RCM at the K-4 plant has not been able to improve the relationship between availability and downtime loss because, after the implementation of RCM, the correlation value K-4 plant has not increased. Even though RCM does increase the availability and reliability (shows from the increase of the mean value of availability and the decrease of the mean value of downtime loss), but there are hidden factors that affect the correlation between those variables to be different from the theory, despite the RCM implementation. Therefore, the company must evaluate further the overall implementation of RCM in K-4 plant, because the statistics show that the implementation of RCM in K-4 plant does not increase the correlation between availability and downtime loss even though the mean value of each variable proves that RCM able to improves the availability and reliability of the plant.

4. Conclusion and Recommendation
Based on the analysis and discussion of the results of research conducted at the four plants in the CSC, it can be concluded that after the implementation of RCM, the availability and reliability of the plants proven to be improved by comparing the mean value of each variable before and after RCM has been implemented. The results of the analysis show that the R-value of downtime loss and availability of K-3 Ammonia and Urea plants are increased, while the R-value of K-4 Ammonia and Urea Plants are decreased. The RCM implemented in K-4 plants should be evaluated respectively, because the decreasing of the correlation means the RCM implementation on the plant still has not met its propose and there are stills hidden factors that affect the availability and downtime loss of the plant, regardless the RCM implementation.

The CSC should conduct a comprehensive evaluation related to the implementation of RCM at K-4 plant so that the correlation between availability and downtime loss becomes more significant. For future research, the implementation of RCM at the K-4 plant can be evaluated thoroughly to improve the effectiveness of the RCM implementation and the hidden factors affecting the correlation of availability and downtime loss could be inspected further.

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