International Journal of Industrial Engineering, 31(3), 472-482, 2024

DEVELOPMENT OF THE RELIABILITY ASSESSMENT IN PREVENTIVE MAINTENANCE OF HEAT, VENTILATION, AND AIR CONDITIONING (HVAC) SYSTEMS FOR THE PRODUCTION OF PHARMACEUTICAL PRODUCT

Adam Ikhwan Zulkiflee[1], Mohd Norzaimi Che Ani[2], Ishak Abdul Azid[3]

[1]Engineering Section
Malaysian Spanish Institute, Universiti Kuala Lumpur
Kulim, Kedah, Malaysia

[2]Manufacturing Section
Malaysian Spanish Institute, Universiti Kuala Lumpur
Kulim, Kedah, Malaysia
Correspondence author's email: mnorzaimi@unikl.edu.my

[3]Engineering Section
Malaysian Spanish Institute, Universiti Kuala Lumpur
Kulim, Kedah, Malaysia

The support system of heat, ventilation, and air conditioning (HVAC) in manufacturing plants plays an important role in the optimum efficiency of the production system. Failure to support adequate HVAC on the production floor will cause production defects, stoppage time, unplanned machine downtime, and other related issues. These issues highly affect those products that require dedicated temperature, pressure, and humidity, such as production clean rooms, food industries, and pharmaceutical products. Thus, this study aims to develop and apply the specific reliability assessment in an investigation of HVAC, focusing on the production of pharmaceutical products. In this study, the selected statistical quality tools have been applied in the evaluation and prediction of the HVAC failure and maintenance process. To ensure suitable tools and methods will be applied, a systematic approach has been developed consisting of six steps towards effective maintenance of the HVAC system. The main purpose of the application quality tools such as check sheet, Pareto chart, scatter plot, and probability plot was to evaluate the historical failure data and then to predict the potential future failure through analysis of Mean Time Between Failure (MTBF) in steps 1 to 4. To ensure the developed approach successfully implemented the Failure Mode and Effects Analysis (FMEA) in step 5, the corrective action plan was suggested in step 6. Once the systematic approach of HVAC preventive maintenance had been successfully developed, it was then implemented in the selected production floor of the pharmaceutical industry. The execution of this developed systematic approach to predicting the HVAC resulted in an increase in the total MTBF from 529.50 minutes to 778.23 minutes. It showed an improvement of 47% after the implementation of the developed systematic approach. The obtained results showed that reliability assessment was important for the optimization of production efficiency.

Keywords: HVAC, Reliability Assessment, Quality Tools, Preventive Maintenance, MTBF, Production Efficiency.

(Received on August 30, 2022; Accepted on May 8, 2024)

1. INTRODUCTION

As the manufacturing industry expands, the demand for building facilities reliability has grown proportionally. The efficiency of heat, ventilation, and air conditioning (HVAC) systems is becoming a significant feature for the productivity and comfortability of the production floor. In general, two approaches can be adopted to make an HVAC system to be more effective on the production floor. The first approach is to design HVAC systems with special regard for redundancy. But this approach involves a lot of cost as it requires two independent HVAC systems set-up consisting of one in operation and the other one in standby mode. This approach is required in cases where the HVAC feature requires a high degree of efficiency, such as telecommunication rooms and production cold rooms (Takakusagi, 1992).

DOI: 10.23055/ijietap.2024.31.3.8563 **ISSN 1943-670X**

The second approach is the preventive maintenance activities that are planned and carried out in isolation in buildings of HVAC systems (Au-Yong *et al.*, 2014). This approach is more economical as it uses the implementation of preventive maintenance. Bortolini and Forcada (2020) presented an efficient preventive maintenance strategy to increase the efficiency and consistency of an HVAC system and its components. Preventive maintenance activities should be able to identify when maintenance work must be carried out to avoid failure. Eti *et al.* (2006) stated that the main purpose of preventive maintenance was to maximize the reliability of components and extend the life of the components. Preventive maintenance can be broken down into preventive maintenance and condition-dependent maintenance based on time. Preventive maintenance based on time is applied mainly to non-repairable goods with a life distribution, and its study and philosophy are known as maintenance policy (Grosso *et al.*, 2020). Condition-based preventive maintenance is applied to such goods where unexpected failure occurs, often called predictive maintenance (González-Domínguez *et al.*, 2020). Since the HVAC system normally breaks down during the life cycle, most of the key HVAC components are compatible with condition-based preventive maintenance. To identify signs of a failure, condition-based prevention maintenance is the method of reducing an emergency stop and maintenance by undertaking preventive measures related to the control of the real-time observation device by the required operating condition and regular maintenance workers inspection.

This requires maintenance of HVAC parts as required by the manufacturer's recommendations and the planning of a regular maintenance schedule for critical assets and facilities. The preventive maintenance program enables the maintenance team to strengthen the scheduling and performance while reducing unplanned breakdowns and losses in production. It is possible to move to preventative maintenance one phase at a time, beginning with the most important properties. Preventive maintenance (or preventative maintenance) is maintenance that is performed regularly on a piece of equipment to reduce the risk of malfunction (Shalabi and Turkan, 2020). It is performed while the equipment is still working so that it does not unexpectedly break down. This lies between reactive (or run-to-failure) maintenance and predictive maintenance in terms of the complexity of this maintenance strategy (Sánchez-Barroso and Sanz-Calcedo, 2019). Preventive maintenance is not based on the state of a system. Instead, it is based on the asset manufacturer's advice or an asset's average life cycle. Rather than on condition, to base maintenance on a calendar can mean that certain maintenance activities are performed when they are not strictly required. But it also ensures that maintenance teams will adhere to the scheduled maintenance activities with the budget, inventory, and schedule to implement. A successful preventive maintenance program has several advantages and helps companies minimize costs while enhancing their practices and activities (Reijula, 2013). Some of the specific improvements resulting from preventive maintenance include extended life of properties and improved uptime for equipment, enhanced efficiency and productivity and decreased paperwork and entry of manual data (Sánchez-Barroso and Sanz-Calcedo, 2019).

As a significant part of the efficiency and comfort of the production floor, the reliability maintenance of HVAC systems must be considered (Mawson and Hughes, 2021). The most critical issues that need urgent attention are to recognize and eliminate the factors that trigger problems at all stages of the life cycle, such as design, maintenance, and quantitative assessment of the reliability model of failure history data. In this case, the maintenance of the HVAC system will affect the production floor, especially in the pharmaceutical industry for example. This is because, for the pharmaceutical industry, humidity and temperature for its products are very sensitive variables and must be controlled at certain values (Kumar and Jha, 2017). Therefore, production efficiency will suffer and have an impact on productivity when the problem occurs within the HVAC system. Due to this situation, the operation of the production floor will be stopped immediately as a product from the pharmaceutical industry requires strict control of temperature and humidity.

Thus, in this paper, a preventive maintenance model based on the reliability assessment of HVAC systems for the production floor of pharmaceutical products is developed. Several quality tools are adopted in the reliability assessment of the HVAC system in this study, such as Check sheets, Pareto charts, Scatter plots, Trend charts, and Failure Mode and Effects Analysis (FMEA). The main objective of the study is to ensure the reliability of the HVAC system in sustaining the production floor operation and minimizing the downtime of the HVAC system. The developed model of preventive maintenance of the HVAC system is described in section 2. This developed model was verified in a selected case study of the pharmaceutical industry and is discussed in section 3, where the key components of HVAC systems analyzed were the compressor, water-cooled chiller, air-cooled chiller, erection type filed for cooling tower, turbo case type of cooling tower, and air handling unit (AHU). Section 4 discusses the results obtained from the application of this developed model.

2. THE METHODOLOGY

Data collection in a production floor involves systematically gathering information about various aspects of the manufacturing process of the pharmaceutical industry located in northern Malaysia, equipment performance, product quality, and other relevant parameters. The methodology for data collection depends on the specific goals and requirements of the organization. A general overview of the methodology for this paper is illustrated in Figure 1.

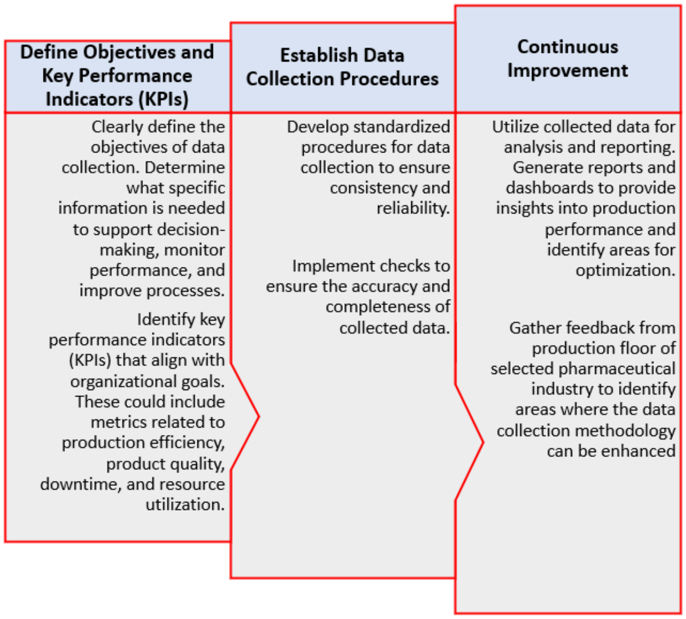

Figure 1. The Methodology of the Systematically Gathering Information

3. PREVENTIVE MAINTENANCE WITH QUALITY IMPROVEMENT TOOLS MODEL

In this study, the preventive maintenance model of HVAC with the application of the selected quality improvement tools has been developed, as illustrated in Figure 2. The purpose of this model is to identify the failure of units and parts and to eliminate or reduce failure in the HVAC components in increasing the reliability of the Mean Time Between Failure (MTBF) result. Quality improvement tools such as check sheet, Pareto chart, scatter plot, probability plot, and Failure Mode and Effects Analysis (FMEA) were employed to define risks of failure in HVAC components, and it helped to establish the impact of failure and to identify and prioritize the action items to alleviate risk. It was initiated before the process of production and maintained through the life cycle of the product. The proposed model in this paper employed quality improvement tools to identify the failure occurrence on each of the main components in the HVAC system in the pharmaceutical industry. The risk assessment using FMEA tracked the progress of preventive maintenance through the reduction in Risk Priority Numbers (RPN) (Yang *et al.*, 2018). A pattern of change and risk reduction could be chronicled by contrasting before and after RPN which was discussed in the section of results and discussion in this paper. For each effect of failure, the severity rating or probability of the effect was identified. Then, the causes and their failure mode mechanisms were established.

To achieve the optimal preventive maintenance of HVAC, six steps have been defined in the developed model as illustrated in Figure 2. The developed model began with the background study of the failure statistic from historical data in step one, and a check sheet was applied to visualize the studied data. The data obtained in Step 1, the data was then analyzed using a Pareto Chart to determine the main factors or main root causes that contributed to the HVAC failure rate. Once the main root causes were identified, the scatter plot was applied in step 3 to study the interaction between two factors which were the failure number versus time consumption. The obtained results of interaction in step 3, were further analyzed in step 4 by using a probability plot to estimate the frequency of failure through MTBF. With the successful estimation of the frequency of failure for the HVAC system, FMEA was then applied in step 5 for the reliability assessment of the HVAC failure rate. This step was useful in determining the policy of maintenance either for fault isolation or fault prevention. However, even though there was no such requirement of FMEA parameters for HVAC systems that would allow the industry to produce FMEA documentation during the maintenance process, these parameters could be determined from many work orders from the industry as this information could only be gathered and collected from the historical data (Yang *et al.*, 2018). Upon completion of all these steps, the corrective action activities could then be executed in the last step to ensure the HVAC system would efficiently support the production system.

In this study, the historical data over the last seven years were collected from the selected pharmaceutical industry. The purpose of this data was to analyze the FMEA parameters. Thus, the operation data corresponding to historical data should have been available. The FMEA in this study concentrated on HVAC at the level of the system or component level. From the point of view of failure mode, the proposed FMEA addressed only the failure modes of hard faults in HVAC systems in operation. The proposed FMEA for HVAC systems included the following key elements for a given failure mode or feature in terms of specification of FMEA parameters such as Failure category, Failure mode, Failure effects, MTBF, and RPN. Some parameters, like MTBF, require more historical data (Ham and Beak, 2018). Fortunately, with the relation of MTBF and RPN from the FMEA method, the process flow of the developed reliability assessment, which included the MTBF calculation, could still be obtained. From the historical data, the failure pattern was examined by analyzing the fault history data for the units and parts of the main HVAC systems in industrial production buildings. In addition, detailed inspections and simplified inspections applied in practical maintenance were developed and the independence between the randomness and inspection of a failure event was investigated. Therefore, the process for determining the optimum inspection period was carried out in this research, where the probability mechanism included the distribution of the probability of condition-based preventive maintenance models in the HVAC system. The data were inspected and analyzed to assess the HVAC system's reliability. The research in this paper only focused on the reliability assessment method of the HVAC system concerning the production department. So, for the first step to overcome these limitations of existing preventive maintenance studies, a method was implemented to achieve the optimum inspection period of preventive maintenance for realistic maintenance, which measured the possible factors not by theories but by random method.

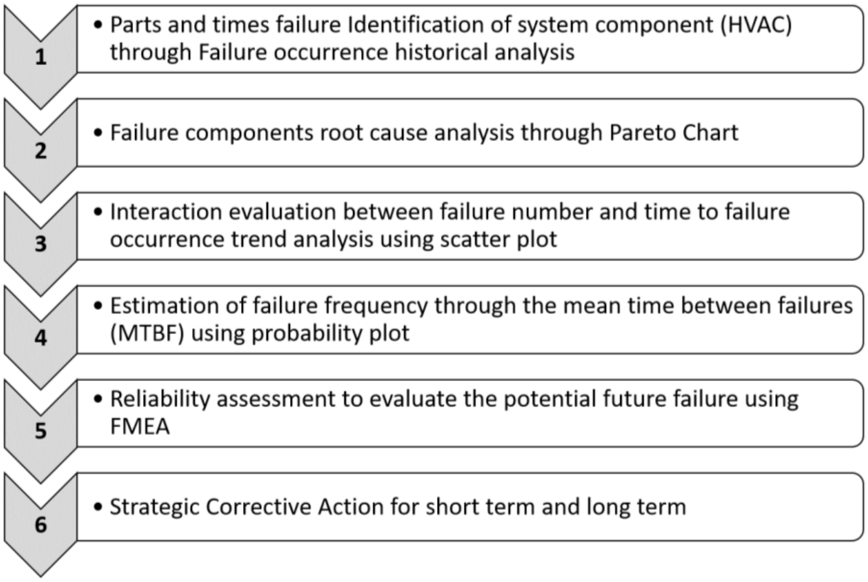

Figure 2. The Preventive Maintenance with Quality Improvement Tools Model

4. DATA COLLECTION AND ANALYSIS

This section presents and discusses the validation of the preventive maintenance with quality improvement tools model through real published production data from the case study industry.

4.1 Case Study

A pharmaceutical industry located in northern Malaysia was selected as a case study industry. The developed preventive maintenance model was validated through an investigation of failure history data of an HVAC component in the pharmaceutical industry HVAC system in this company. Recording failure data in a production environment involves systematic data collection and analysis to identify patterns, trends, and root causes of failures. In terms of health parameters responsible for most failures, it can vary depending on the industry and specific equipment. Regularly analyzing failure data and health parameters helps organizations implement proactive maintenance strategies, reduce downtime, and enhance overall system reliability. This pharmaceutical company had 5 units of air handling units with 79.084 kW each, two chillers with 2461.7775 kW each, 1587.495 kW of cooling tower field erection type, 3401.775 kW of turbo case type of cooling tower, and 62.086kW compressor as stated in Table 1.

Table 1. HVAC Components in Production Building

Component	Capacity and quantity	Type and special feature
AHU	79.084 kW x 5	Air foil 4 ss (cooling capacity)
Chiller	2461.7775 kW x 1 2461.7775 kW x 1	Water cooled chiller Air cooled chiller
Cooling tower	1587.495 kW x 2 3401.775 kW x 2	Field erection type Turbo case type
Compressor	62.086 kW x 1	-

4.1 Data Collection and Analysis

This section describes the data collection and analysis for the developed model as presented in Section 2. The data collection started with the background study of the failure statistics from historical data in step one, where the data was recorded into a check sheet as tabulated in Table 2. The main purpose of this step was to ensure this study would focus on the right issues that impacted the efficiency of the production floor. Before assessing the reliability assessment for HVAC components, the yearly mean operation time of HVAC components and the failure occurrence needed to be analyzed. It was because not all the components had a high tendency to fail and needed to be monitored depending on the failure rate of the component. In this research, only one HVAC component with the highest ratio was taken as the outcome in step 1 for further analysis. Table 2 shows the failure occurrence data of HVAC main components, including the external compressor, water-cooled chiller, air-cooled chiller, cooling tower (field rection type) and turbo case type, and air handling unit (AHU) for 6 years from 2013 to 2019.

Table 2. Failure Occurrence Number and Operation Time (unit: number, hour)

Year	**External Compressor**	**Chiller**		**Cooling Tower**		**AHU**	**Sum of occurrence number**
		Water Cooled chiller	Air cooled chiller	Field erection type	Turbo case type		
2013	0	0	0	0	0	1	1
2014	4.7	3.2	6.7	0.9	4.3	0.8	21
2015	9.3	4.3	10	0.9	3	0.3	24.5
2016	8.4	4.7	8	0.9	4.5	1	27.6
2017	6.8	7.5	13	1.4	1.5	0.2	28.7
2018	5.6	4.8	12	1.2	0.7	0.9	23.6
2019	4.7	2.8	5.7	2.5	0.7	0.4	15.7
Average	5.6	3.9	7.8	1.2	2.1	0.7	21.3
Ratio	26%	18%	37%	5.6%	9.8%	3.1%	100%
Operation time	1229	849	1225	0	0	0	0

The failure occurrence data as in Table 2, shows the average value from 6 years for each of the main components of the HVAC system in one unit per year with the operation time. The ratio value in percentage is the most important data as it shows the main components with the highest or lowest value, which need to be selected for the next investigation of this research. Then, the sum of failure occurrences for each main component in one year is stated. Based on Table 2, the chiller has the highest value in ratio with 55%. Thus, the chiller was selected to be analyzed by using the developed reliability assessment method as in this paper.

From the result obtained in step 1, further analysis was conducted in step 2 where the failure of units and parts in the chiller was scrutinized and then identified by using the Pareto chart. The method in step 2 counted the total failure frequency of the components or parts in the chiller and their failure occurrence ranking and cumulative distribution. These data of failure were obtained to calculate the cumulative count and the cumulative percentage from the maintenance routine for one year. Table 3 and Figure 2 show the data collection for the number of failures in a year and the failure characteristics of the components or parts in a chiller. The data collection in Table 3 also states the highest number of failures with its cumulative count and percentage. The part with the highest number of failures was identified for the next step of the reliability assessment method, which, for this study, identified part was the compressor with 424 failures. Then, the principle of the 80-20 rule was applied from the chart obtained, as shown in Figure 3. This 80-20 rule defined and effectively used the best assets of an organization to achieve full profit. For explanation, 80 percent of results (outputs) came from 20 percent of triggers (inputs). The focus of this step was to identify the highest frequency failure of the HVAC sub-component from the Pareto chart obtained, which was analyzed from the 20 percent of failure effect. In this research, only one part or component that had the highest frequency that led to failure was chosen for further analysis. As tabulated in Table 3, the chiller compressor with 424 number of failures was identified.

Table 3. Data collection number of failures in a year in parts of chiller

Parts	**No. of failures**	**Cum. count**	**Cum. %**		**Parts**	**No. of failures**	**Cum. count**	**Cum. %**
Compressor	424	424	25%		Motor	105	1397	82%
Condenser coil	252	676	39%		Oil Heater	84	1481	87%
Evaporator coil	231	907	53%		HX Coolant	77	1558	91%
Expansion valve	147	1054	62%		Oil Pump	77	1635	96%
Filter	126	1180	69%		Heat Exchanger	77	1712	100%
Gears	112	1292	75%		**Total**	**1712**		

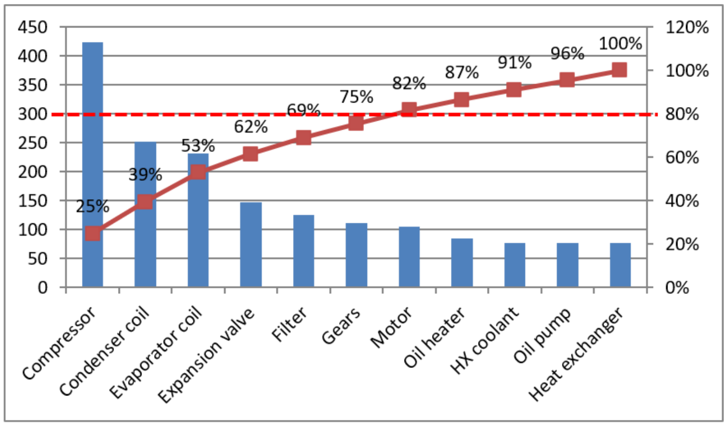

Figure 3. Failure characteristics of chiller using Pareto diagram

Once the main root cause was identified from the Pareto chart, then in step 3, an examination of the failure patterns would determine whether the failure of the parts indicated a pattern of spontaneous failure or a pattern of wear-out failure. This examination could be broken into the methods of graphical analysis and empirical analysis. The approach of graphical analysis analyzed the frequency of failure occurrences based on a change in the object facility over time. The empirical method analyzed the interval calculation for the Weibull distribution shape parameter and tested the reliability of the random failure by regarding the estimated segment including 1.0 as a random failure pattern, while the estimated interval exceeds 1.0 as a wear-out failure pattern.

Reliability is a critical aspect of many systems and is often characterized by metrics such as Mean Time Between Failures (MTBF), Mean Time to Failure (MTTF), and Mean Time to Repair (MTTR). These metrics help assess the performance and availability of systems. Statistical probability tests are commonly used to evaluate and estimate these reliability metrics. Statistical probability tests are crucial for assessing and estimating reliability metrics such as MTBF, MTTF, and MTTR. The choice of statistical methods depends on the nature of the system, the type of data available, and the assumptions made about the underlying probability distributions.

In this paper, both methods were employed in analyzing the failure trend of the part. Table 4 shows the failure occurrence trend of the chiller's compressor obtained from the case study industry and the resulting calculation through Weibull distribution from reliability analysis. From Table 4, failure number and time in hours of operation hours were identified. Then, the calculation of the failure ratio number, F, could be determined from equation (1) (Wang and Loman, 2002). The rate of failure event analysis based on a shift of the study object facility over time using the trend analysis method (Chaplin *et al.*, 2004) is as shown in equations (2) and (3).

$$F = (\text{average failure every hour per year} - 0.5) / \text{number of samples, } n \tag{1}$$

$$\text{Time to failure} = \ln(\text{average failure every hour per year}) \tag{2}$$

$$\text{Failure number, } \ln[N(t)] = \ln[\ln(1/F)] \tag{3}$$

Table 4. Failure Occurrence Trend of Chiller's Compressor

Week	No. of failures	time (h)	MTBF	Rank	Failure every hour per year	F	"x" ln[time at failure]	"y" ln[ln(1/(1-F))]
1	6	2190	365.000	1	115.2632	0.03846	4.74722	-3.23855
2	7	2190	312.857	2	136.875	0.11539	4.91907	-2.09881
3	11	2190	199.091	3	136.875	0.19231	4.91907	-1.54377
4	16	2190	136.875	4	182.500	0.26923	5.20675	-1.15945
5	6	2190	365.000	5	199.0909	0.34615	5.29376	-0.85594
6	10	2190	219.000	6	199.0909	0.42308	5.29376	-0.59775
7	16	2190	136.875	7	219.000	0.5000	5.38907	-0.36651
8	2	2190	1095.00	8	243.3333	0.57692	5.49443	-0.15059
9	19	2190	115.263	9	312.8571	0.65385	5.74575	0.059091
10	12	2190	182.500	10	365.000	0.73077	5.89990	0.27170
11	9	2190	243.333	11	365.000	0.80770	5.89990	0.49997
12	11	2190	199.091	12	438.000	0.88462	6.08222	0.76987
13	5	2190	438.00	13	1095.000	0.96154	6.99851	1.18114

From data obtained data in Table 4, the scatter plot was used to find the interaction between failure number versus time to failure occurrence trend analysis as shown in Figure 3 when all the data had been calculated. All the data obtained from the calculation except MTBF were keyed in Table 4. MTBF calculation will be explained in the following paragraph.

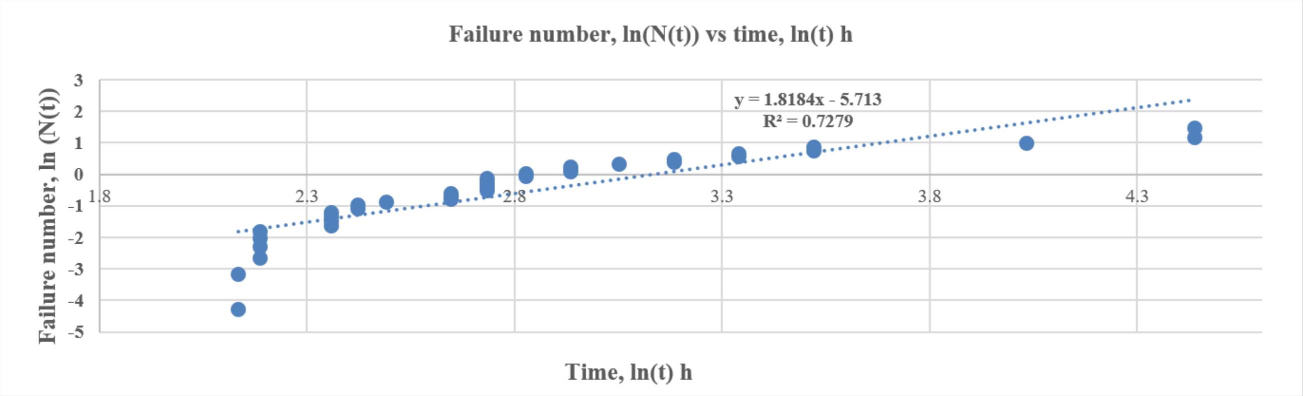

Figure 3. Failure occurrence trend graph analysis of the chiller's compressor

In step 4, the estimation of failure frequency through the mean time between failures (MTBF) using a probability plot was carried out by analyzing the failure trend and reliability using Weibull's probability graph paper to assess whether the items failed to display a pattern of random failure or a pattern of wear-out failure. The wear-out curve consists of a low level of random failures, preceded at the end of its life by a sharp rise in failures. Approximately 2 percent of failures were accounted for as wear-out failures, while random failures accounted for 68 percent of failures account for this trend. The average time between system breakdowns was the mean time between failures (MTBF). To measure efficiency, protection, and equipment design, MTBF was a crucial maintenance metric, especially for critical or complex properties, such as generators or airplanes. Normally, MTBF is measured in hours. The calculation of MTBF was as follows. Table 5 shows the MTBF values for the chiller's compressor.

MTBF = Number of operational hours, h / number of failures (4)

Table 5. Chiller's compressor for MTBF value

Week	No. of failures	Time (h)	MTBF	Week	No. of failures	Time (h)	MTBF	Week	No. of failures	Time (h)	MTBF
1	6	169	28.2167	15	19	169	8.911	29	11	169	15.39
2	7	169	24.1857	16	15	169	11.29	30	2	169	84.65
3	11	169	15.3909	17	12	169	14.11	31	19	169	8.911
4	16	169	10.5813	18	12	169	14.11	32	5	169	33.86
5	6	169	28.2167	19	19	169	8.911	33	7	169	24.19
6	10	169	16.930	20	8	169	21.16	34	14	169	12.09
7	16	169	10.5813	21	9	169	18.81	35	16	169	10.58
8	2	169	84.650	22	15	169	11.29	36	10	169	16.93
9	19	169	8.91053	23	11	169	15.39	37	9	169	18.81
10	12	169	14.1083	24	3	169	56.43	**Total**	**424**	**6264**	**773.9**
11	9	169	18.8111	25	11	169	15.39				
12	11	169	15.3909	26	11	169	15.39				
13	5	169	33.86	27	20	169	8.465				
14	20	169	8.465	28	16	169	10.				

As shown in Table 5, the obtained total MTBF is 773.9477 minutes. This MTBF value would then be used to define the possible root cause and potential countermeasure in step 5 in assessing failure parts using FMEA. Based on the historical data from the company, two failure modes had been identified which were the system always shutting down by itself and the command window screen frequently cracked. Both failure modes were evaluated based on the rating of Severity (S), Occurrence (O), and Detection (D) to calculate the Risk Priority Number (RPN), where the rating of the (S), (O), and (D) was based on the scale of 1 to 10 and RPN was then calculated by using equation (5) (Yesmin *et al.*, 2013). The RPN is a numerical assessment used in FMEA to prioritize and rank potential failure modes based on their perceived risk. The RPN is calculated by multiplying three factors: S, O, and D. It's important to note that while the RPN provides a systematic way to prioritize risks, it has some limitations. The subjectivity of assigning ratings and the lack of consideration for dependencies between factors can affect the accuracy of the results. Teams should use RPN as a tool for discussion and decision-making rather than as a definitive measure of risk. The result of FMEA is as shown in Table 6.

RPN = S x O x D (5)

Table 6. Example of FMEA for compressor

Component	Parts	Failure Mode	Effects	**S**	Causes	Prevention Control	**O**	Detection Control	**D**	**RPN**
Chiller	Compressor	The system always shutting down by itself	The production stop	**8**	Not enough power to generate it for a long period	Increase inspection time	**8**	Engineer check after maintenance	**4**	**256**
		The command window screen of the compressor cracked	Disturb the inspection process	**5**	Exposed to sunlight	Cover it using window cover	**3**	Engineer check after maintenance	**4**	**60**

Based on Table 6, the calculated RPN for the system always shutting down by itself was 256, as calculated using equation (5), and that for the command window screen frequently cracked was only 60. The obtained results meant the main factor that contributed to the MTBF 773.9477 minutes was the system always shutting down by itself. The next step would be to discuss how the defined root cause would be eliminated or minimized to improve the MTBF. Once the main root cause has been identified from FMEA analysis, the corrective action in step 6 will be proposed and implemented. The system always shutting down by itself is expected from the failure of the electrical supply or intermittent electrical trips, and the proposed solution is re-wring the chiller room to ensure the solving of the defined issue. Since the high loss cost of the production process due to insufficient support from HVAC, the management has agreed and implemented the proposed solution and it was implemented immediately during production shutdown.

5. RESULTS AND DISCUSSIONS

After the proposed model has successfully been verified and validated in a case study industry, the proposed solution was implemented in the same case study industry. HVAC is one of the crucial processes in any industry because providing effective cooling for buildings and industrial facilities at minimum cost is one of the main challenges in the HVAC industry (Pargas *et al.,* 2022). Based on that situation, mathematical problems and a multi-component structure crashworthiness design application are tested to show considerable improvements of MTBF. This similar method also has been verified with the success of the study by Li *et al. (2019)* from the article of a moving shifting vector method for reliability-based design optimization using effectiveness checking of probabilistic constraint. Table 9 shows the result after applying the optimal preventive maintenance with reliability assessment for production. The observation was made for 26 weeks, and the downtime data was recorded in Table 7. The recorded data after implementing the corrective action showed that the total MTBF was 778.23 minutes compared with the first 26 weeks before improvement (Table 5 – by taking up to 26 weeks), which was 529.50 minutes. It showed an improvement of 47% after the implementation of the corrective action. The number of failures and the number of downtimes reduced which would indirectly improve the lifetime of the chiller's component. The comparison between the data of MTBF before and after the implementation of the corrective action is shown in Figure 4.

Table 7. The data of MTBF after implementation of the corrective action.

Week	**No. of failures**	**time (h)**	**MTBF**		**Week**	**No. of failures**	**time (h)**	**MTBF**
1	6	169.3	28.21667		14	3	169.3	56.43333
2	7	169.3	24.18571		15	7	169.3	24.18571
3	11	169.3	15.39091		16	6	169.3	28.21667
4	16	169.3	10.58125		17	3	169.3	56.43333
5	6	169.3	28.21667		18	5	169.3	33.86
6	10	169.3	16.93		19	7	169.3	24.18571
7	16	169.3	10.58125		20	4	169.3	42.325
8	2	169.3	84.65		21	8	169.3	21.1625
9	19	169.3	8.910526		22	5	169.3	33.86
10	12	169.3	14.10833		23	8	169.3	21.1625
11	9	169.3	18.81111		24	4	169.3	42.325
12	11	169.3	15.39091		25	4	169.3	42.325
13	5	169.3	33.86		26	4	169.3	42.325
					TOTAL			**778.23**

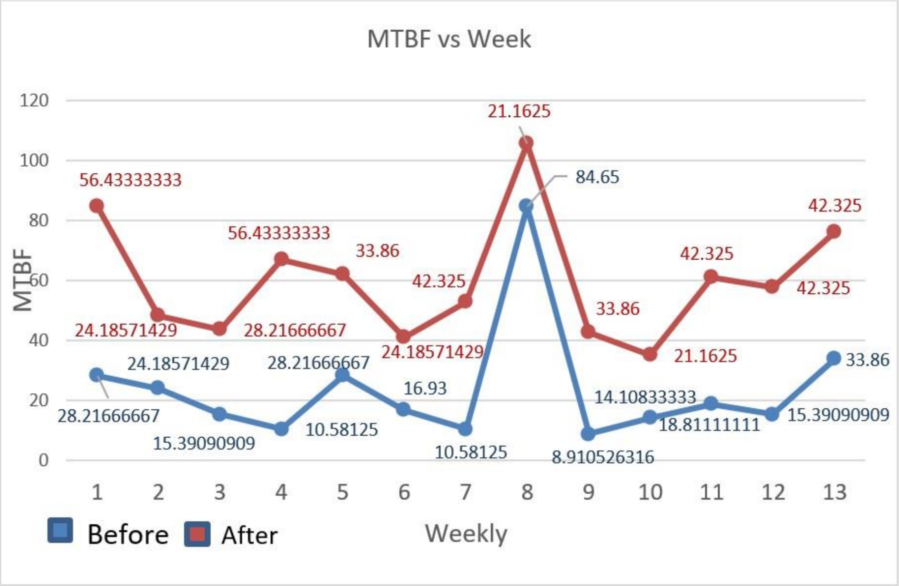

Figure 4. Trend graph of MTBF vs week before and after the implementation of the model

6. CONCLUSION

The development of an optimal preventive maintenance model based on the reliability assessment for heat, ventilation, and air conditioning (HVAC) systems for production has been successfully executed with the combination of quality improvement tools and methods. Check sheets, Pareto charts, Scatter plots, trend analysis graphs, MTBF calculations, and FMEA have been applied in this study towards optimum efficiency and reliability of the HVAC system to support the production floor. The developed model improved the efficiency of the HVAC in terms of increasing mean time between failure (MTBF) based on the obtained results of the implementation in selected production plants where the MTBF increased drastically to approximately 40% from comparison between historical data and data after implementation. The parameter of MTBF is important to identify the average of failure by estimation of the component's lifetime. MTBF with a higher value shows a higher tendency time for the component or part to operate before its failure. As a result of the failure pattern analysis of the units of the chiller in the HVAC system tested, consisting of the compressor, evaporator coil, expansion valve, and gears, it is shown that not only the units are prone to wear out failure but most of the components are also prone to the same pattern. Therefore, it has been discovered that the condition-based maintenance policy implementing preventive maintenance, which preliminarily predicts failure, is suitable for HVAC systems. Furthermore, by estimating the MTBF for the units and sections and the failure time distribution parameter, the failure characteristic was grasped. Finally, this optimal preventive model can be used not only in production but other industries or departments using air conditioning systems. This developed model will affect the rise of productivity as it ensures the maintenance or failure of the component does not interrupt the production process.

REFERENCES

Au-Yong, C. P., Ali, A. S., & Ahmad, F. (2014). Improving occupants' satisfaction with effective maintenance management of HVAC system in office buildings. *Automation in Construction*, 43(1): 31-37.

Bortolini, R., & Forcada, N. (2020). Analysis of building maintenance requests using a text mining approach: Building services evaluation. *Building Research & Information*, 48(2): 207-217.

Chaplin, G., Pugsley, T., & Winters, C. (2004). Application of chaos analysis to pressure fluctuation data from a fluidized bed dryer containing pharmaceutical granule. *Powder Technology*, 142(2-3): 110-120.

Eti, M. C., Ogaji, S. O. T., & Probert, S. D. (2006). Development and implementation of preventive-maintenance practices in Nigerian industries. *Applied energy*, 83(10): 1163-1179.

González-Domínguez, J., Sánchez-Barroso, G., & García-Sanz-Calcedo, J. (2020). Scheduling of Preventive Maintenance in Healthcare Buildings Using Markov Chain. *Applied Sciences*, 10(15): 5263.

Grosso, R., Mecca, U., Moglia, G., Prizzon, F., & Rebaudengo, M. (2020). Collecting built environment information using UAVs: time and applicability in building inspection activities. *Sustainability*, 12(11): 4731.

Ham, Y. H., & Beak, Y. K. (2018). An Objective Method of Risk Evaluation based on RAM (Reliability, MTBF) and AHP Data Analysis for Warship. *Journal of the Korea Institute of Military Science and Technology*, 21(5): 714-721.

Kumar, N., & Jha, A. (2017). Temperature excursion management: A novel approach of quality system in pharmaceutical industry. *Saudi Pharmaceutical Journal*, 25(2): 176-183.

Li, X., Xu, F., Qiu, H., Chen, Z., He, W., & Ma, J. (2019). A Moving Shifting Vector Method For Reliability-Based Design Optimization Using Effectiveness Checking Of Probabilistic Constraint. *International Journal of Industrial Engineering: Theory, Applications and Practice*, 26(1).

Mawson, V. J., & Hughes, B. R. (2021). Optimisation of HVAC control and manufacturing schedules for the reduction of peak energy demand in the manufacturing sector. *Energy*, 227(1): 120436.

Pargas-Carmona, L. A., Da Silva, J. A., Sant'Anna, Â. M., and Risco-Martín, J. L. (2022). An optimization scheme for chiller selection in cooling plants. *Journal of Building Engineering*, 49(1), 104066.

Reijula, J., Holopainen, R., Kähkönen, E., Reijula, K., & Tommelein, I. D. (2013). Intelligent HVAC systems in hospitals. *Intelligent Buildings International*, 5(2): 101-119.

Sánchez-Barroso, G., & Sanz-Calcedo, J. G. (2019). Application of predictive maintenance in hospital heating, ventilation and air conditioning facilities. *Emerging Science Journal*, 3(5): 337-343.

Shalabi, F., & Turkan, Y. (2020). BIM-energy simulation approach for detecting building spaces with faults and problematic behavior. *J. Inf. Technol. Constr*., 25(1): 342-360.

Takakusagi, A. (1992). Analysis on effect of reliability improvement and economy of condition based preventive maintenance. Analytical study on preventive maintenance of air-conditioning system part 2. *Journal of Architecture Planning and Environmental Engineering*, 441(1): 43-52.

Wang, W., & Loman, J. (2002, January). Reliability/availability of K-out-of-N system with M cold standby units. *In Annual Reliability and Maintainability Symposium. 2002 Proceedings (Cat. No. 02CH37318)* (pp. 450-455). IEEE.

Yang, C., Shen, W., Chen, Q., & Gunay, B. (2018). A practical solution for HVAC prognostics: Failure mode and effects analysis in building maintenance. *Journal of Building Engineering*, 15(1): 26-32.

Yesmin, T., Hasin, M., & Proma, F. (2013). Assessment of worker safety in a pharmaceutical industry using FMEA. *Management Science Letters*, 3(1): 55-64.