International Journal on Advanced Science Engineering Information Technology

Vol.12 (2022) No. 4
ISSN: 2088-5334

Using Failure and Repair Data for System Improvement in Plant Facilities

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Abstract—**Previous research has emphasized the need to identify the cooling tower's critical components and parts in order to evaluate the system's performance. From a reliability point of view, a cooling tower is considered a series system. There is a redundant unit for some equipment to maintain availability and ensure the equipment carries out its intended function. The main objective of this study is to identify the critical component or parts of the cooling tower and evaluate system performance. Based on a scientific way: reliability, availability, and maintainability (RAM) analysis, the critical component of a cooling tower is investigated using RAM prediction indices. This paper deals with a case study conducted in a cooling tower plant. Both ERP extracted files, and maintenance log-book have been confirmed to maintenance personnel and maintenance monthly report to verify failure event and repair time. According to the results, the system performance (cooling tower) of the system availability is 93.91 percent. There is still an opportunity for a 6.09 percent system performance increase to be implemented on critical subsystems. The emphasis of crucial subsystem maintenance will be solely on the weakest components. Pareto charts and RAM analysis show that pump performance should be prioritized on essential components, such as packing seals or grand packing. The performance results obtained by upgrading are predicted to be 95.6725 percent. This paper proposes a method for identifying the weakest component or part based on failure and repair data. The weakest component will be the focus of future system performance improvements.**

Keywords— **Cooling system; reliability; availability and maintainability analysis; system improvement; system performance.**

Manuscript received 20 May 2021; revised 14 Sep. 2021; accepted 18 Oct. 2021. Date of publication 31 Aug. 2022.

I. INTRODUCTION

Plant failures are mostly caused by improper maintenance and the inability to predict maintenance problems [1]. In an automatic production line, unexpected equipment failure or parts damage can be very expensive. As a result, it contributes to unscheduled downtime costs and spare parts due to recommended corrective action [2]. Therefore, a system's measurement and improvement are critical due to its significant impact on achieving economic performance [3] and meeting financial goals [1].

Reliability, availability, and maintainability (RAM) are system characteristics that have a significant contribution total life cost of an equipment or system [4]. It has an important role in a system [5]. The effectiveness of the production system and the equipment is measured and determined based on reliability and availability value [6]. As one of the engineering tools, RAM analysis has been developed to significantly impact the system performance and its improvement [3]. RAM is believed to be one of the significant areas for profitability improvement, and it can also be a significant contributor to improving safety and environmental performance [7].

A reliability index or value is one method to identify a critical subsystem and provide a numerical value to determine the weakest parts and components critical for system performance [8]. The knowledge of reliability is necessary for reducing unplanned downtime costs as well as increasing system performance [9]. The use of an outstanding reliability program will ensure the maintenance data as crucial information regarding the system performance and direct the use of this information to be investigated by management [1].

While this term of reference is not new, the corresponding study related to reliability, availability, and maintainability analysis for the cooling system area is quite limited. Further, it has been found that most researchers only focus on general availability [2]. A cooling tower is a water treatment system that provides cooled water (CW) with a certain quality and quantity of CW. It provides the necessity of cooled water for the ammonia and urea plant. It consists of three pieces of equipment, i.e., a make-up pump, induced draft fan, and circulation cooled water (CW) pump. To maintain availability, both induce draft fan, and circulation CW pump has redundancy system including one standby unit. Both induced draft fan and circulation CW pump comprise the three-equipment system, including two online units and one standby unit.

Under the assumption that failure and repair rates are constant at a specified period, this study measures the cooling tower system's reliability, availability, and maintainability. To calculate the operational availability of equipment with a redundant unit, the time between failure (TBF) and time to repair (TTR) of equipment is assumed to follow an exponential distribution. The study aims to improve the system performance of the cooling tower plants based on RAM evaluation. Therefore, the objectives of this research are as follows:

- Identify the critical component or parts of the cooling tower.
- Evaluate the system performance. Predict the performance improvement of critical equipment and components that contribute the most to system or production line failure.

II. Materials and Methods

The research begins with a literature study related to system performance measurement and maintenance actions. After that, the objectives and formulation of research problems are formulated to go to the next stage. Studies on several approaches to research methods are also carried out to find suitable methods. The next step is identifying system performance and maintenance performance on the research object. Identification can be obtained from the KPI for the maintenance and operation division units. Some indicators of problems include unsatisfactory production targets and minimization of unscheduled shutdowns that are not yet optimal. Field studies were also carried out better to understand the process flow from start to finish. In-depth knowledge of equipment functions and problems is also explored in this process.

Based on maintenance data, TBF and TTR will be calculated from the repair data and failure data that have been collected. TBF and TTR will then be used as random variables in calculating the RAM index of the equipment. The RAM index will show critical equipment in production line systems, water treatment plants, and cooling towers. The determination of the performance improvement space will be based on the weakest components of the critical equipment found. The maintenance measures or actions will focus on improving the weakest components' performance to improve the current system performance.

Tsarouhas [1] defines reliability as the probability of non-failure or free failure in a given time period. In other words, reliability is the probability that a subsystem or system will perform an intended function, under specific conditions, for a stated period t. Reliability is measured as a probability. The reliability of the equipment analyzed using the probability theory can be in the form of individual components in a system, such as gate valves and ball bearings, or the system itself may consist of many components [10].

To reduce unexpected equipment failure costs, it is important to have high equipment reliability [11]. If the failures persist in the plant at high frequency, it will decrease production and limit gross profits. Improving reliability involves reducing the frequency of failure. A study published by [3] provides an operation to measure the probability for failure-free, it is often shown as:

$$R(t) = exp\left(-\frac{t}{MTBF}\right) = exp(-\lambda t) \tag{1}$$

Several key parameters defining reliability are the mean time between failure (MTBF), mean time to failure (MTTF), failure rate, and a number of failures [3].

Maintainability deals with the repair time or breakdown duration. It shows how long the maintenance action takes and how easy it is to achieve excellent conditions. High or excellent maintainability means the system has predictable and short repair time. Excellent maintainability shows the effectiveness of the system [3]. Maintenance performance means the ability of equipment under specified operating conditions to be restored or retained in a state in which the equipment can perform intended functions when maintenance action is performed using recommended procedures and resources. Also, it can be considered as the ease of maintenance and repair actions [4].

$$M(t) = 1 - \boldsymbol{exp}\left(-\frac{t}{MTTR}\right) = 1 - \boldsymbol{exp}(1 - rt) \tag{2}$$

where r and MTTR are defined as repair rates and mean time to repair (breakdown duration), respectively [3].

Availability has been considered a valuable performance measure for many industrial systems. Paper [5] concludes that availability can be increased by the improvement of both reliability and maintainability. High maintainability is related to ease of maintenance action when performed as recommended procedures. High reliability and high maintainability show that the system is in effective condition. Availability is related to both reliability and maintainability. It is determined as follows [3]:

$$\boldsymbol{A} = \frac{\boldsymbol{MTBF}}{(\boldsymbol{MTBF}+\boldsymbol{MTTR})} \tag{3}$$

$$T = \begin{bmatrix} -(\lambda_1+\lambda_2+\bar{\lambda}_3) & r & r & r & . & . & . & . \\ \lambda_1 & -(\lambda_2+\lambda_3)-r & . & . & r & . & r & . \\ \lambda_2 & . & -(\lambda_1+\lambda_3)-r & . & r & r & . & . \\ \lambda_3 & . & . & -(\lambda_1+\lambda_2)-r & . & r & r & . \\ . & \lambda_2 & \lambda_1 & . & -\lambda_3-2r & . & . & r \\ . & . & \lambda_3 & \lambda_2 & . & -\lambda_1-2r & . & r \\ . & \lambda_3 & . & \lambda_1 & . & . & -\lambda_2-2r & r \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

Fig. 1 Probability plot of TBF cooling tower

In general, availability could be considered the most important parameter or system characteristic as it is related to the system's productivity [4]. In addition, as a method that improves the availability of the system, redundancy plays a crucial and important role, and that redundancy system mainly includes a parallel system [6]. Fig. 1 explains how matrix operation can be used to determine the steady-state availability solution of a three-equipment system (two online units and 1 standby unit) [7].

Several industries have successfully implemented methodologies involving reliability, availability, and maintainability [8]. Furthermore, reliability, availability, and maintainability, which were initially used in the gas and oil industry, are now starting to carry out in extensive studies in various fields, including the food industry [1], [12], [13], thermal power plant [14], transportation [15], and infrastructure [16] and plastic industry [17]. Analyzes involving reliability, availability, and maintainability were carried out [1], [12], [13],[18]–[20] in evaluating subsystem performance with different industry case studies.

Barabady [21] estimates reliability and maintainability characteristics with a statistical method approach in determining maintenance intervals and critical components and subsystem performance in a plant. Meanwhile, Wang et al. [2] and Choudhary et al. [19] propose reliability and availability estimation using the Markov model approach to evaluate a cooling system's performance. Studies on reliability and availability were also carried out [22] in evaluating belt drive systems. Analysis of reliability, availability, and maintainability was carried out [1], [10], [15], [16], [17] in evaluating subsystem performance with case studies of different industries. Tsarouhas [13] and Barabady [21] analyze these three characteristics in the safety area by adding safety characteristics in rail transportation applications.

The literature shows that most existing models or complex calculations only focus on the availability and/or reliability parameters. Meanwhile, other authors only focus on reliability and maintainability related to performance measurement and evaluation of critical components of several industrial systems. Meanwhile, maintainability and dependability parameters have not been touched [17], [18], [19]. Aggarwal et al. [23] consider the need for additional parameters to evaluate system performance. This research will evaluate the performance of the subsystems involving reliability, availability, maintainability, and dependability. With the addition of parameters, it is hoped that this study can fill the limitations of the literature in terms of maintainability and dependability.

Determining the critical equipment may be difficult in conditions where a system has so much equipment. Some devices may have the same RAM index value (reliability, availability maintainability). The addition of the dependability parameter can support the determination of the weakest component, which is the room for improving system performance. These parameters can make it easier to determine critical equipment in industrial systems.

This paper deals with a case study conducted in the cooling tower plant to investigate the reliability and availability value of the plant. Both circulation CW pump and induced draft fan are considered as a series system, and both have two online and standby units to perform the intended function in the operating state. Two pumps are considered a series system without a standby unit for the make-up pump (2205-JMA and 2205-JMB).

The cooling tower system operates twenty hours per day and eight hours per shift to meet the need for urea and ammonia plant water. The cooling tower plant records failure and repair data for about two-and-a-half years of operation.

Performance evaluations on cooling towers were obtained from data collection on failure and repair during the 3-year operating period. The main data is ERP data which is extracted into Microsoft Excel files. Raw data from ERP that has been extracted is an important part of the research. These data will produce TBF and TTR for equipment and critical components. The analysis and conclusions were drawn based on the outputs generated from TBF and TTR data processing. Production/operations and maintenance departments can use the output of this study as material for evaluation and improvement to achieve better production targets and KPI values.

Both ERP extracted files and maintenance log-book has been confirmed to maintenance personnel and maintenance monthly report to verify failure event and repair time. Further, the particular equipment's failure rate and repair rate are collected to provide RAM analysis [24]. TBF and TTR data as random variables at the cooling tower system has been accurately determined based on the method.

The main steps of methodology performed in the RAM framework are as follows. The following steps are performed to result in RAM analysis:

- TBF calculation based on collected failure data. The failure events are collected from the ERP cooling tower. Two adjacent failure events result in TBF as a random variable
- TTR calculation based on collected repair data. TTR data are determined based on the breakdown duration of particular equipment
- Scale parameter (β) is determined based on the assumption that TBF and TTR follow exponential distribution [5]
- Reliability analysis is carried out to predict system characteristics, including MTBF and failure rate of equipment
- Availability analysis is carried out to predict system availability considering a redundant unit. The operational availability refers to induced draft fan and circulation CW pump that have a redundant unit in normal operation
- The final step is determining critical equipment. Based on system characteristics, i.e., reliability and availability, the critical equipment is determined considering MTBF, failure rate, and operational availability.

III. Results and Discussion

A. *Identifying The Critical Component or Parts of The Cooling Tower*

As a cooling system, the cooling tower allows hot water and air to come in contact to reduce the temperature of hot water (±42°C). Hot water produced by the ammonia and urea plant enters the cooling tower's top deck and then drops. As a result of contact, the process of removing heat by airflow and evaporation of some water by releasing latent heat. Water that has become cold is accommodated in the cooling tower basin and reused as cooling water. Coldwater from the basin is sent to the plant using a two-unit circulation CW pump (2209-JAT and 2209-JCM) and one standby unit (2209-JBT).

Due to the evaporation of water during the cooling process, the basin must be added with water (make-up process) to replace the lost water. The making-up process in the basin is performed by two make-up pumps (2205-JMA and 2205-JMB). Fig. 2 depicts the schematic cooling tower and block diagram. Table 1 shows the Anderson-Darling statistics value and the probability plot (Fig. 3–4).

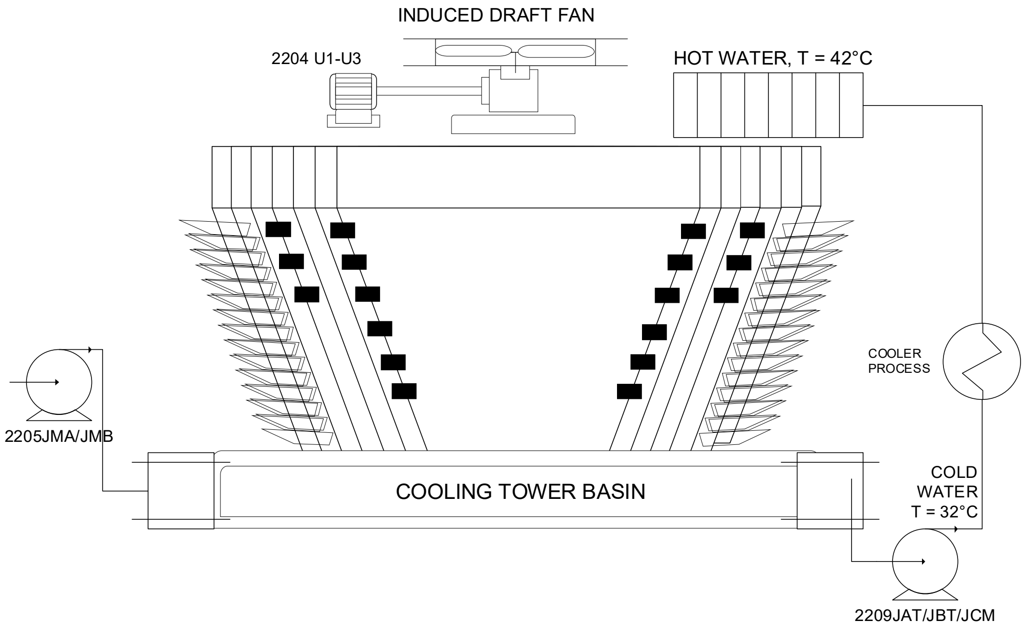

Fig. 2 Schematic cooling tower

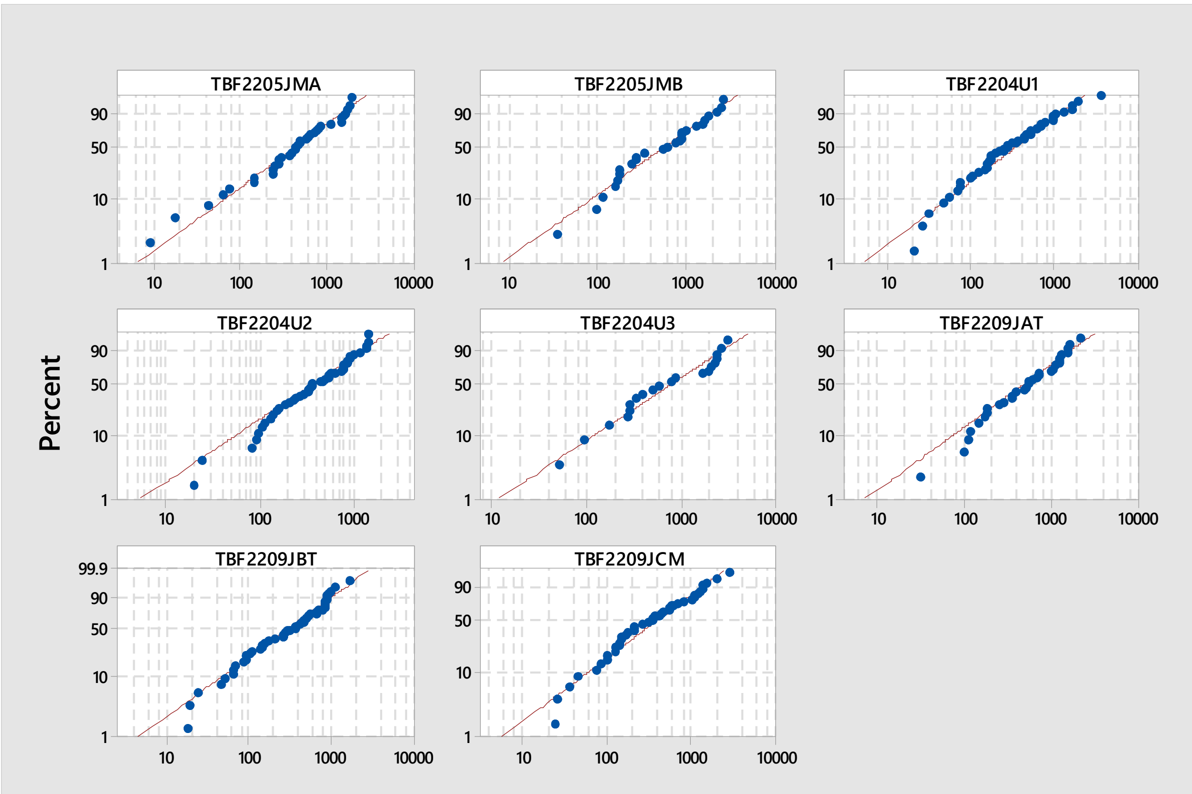

Fig. 3 Probability plot of TBF cooling tower

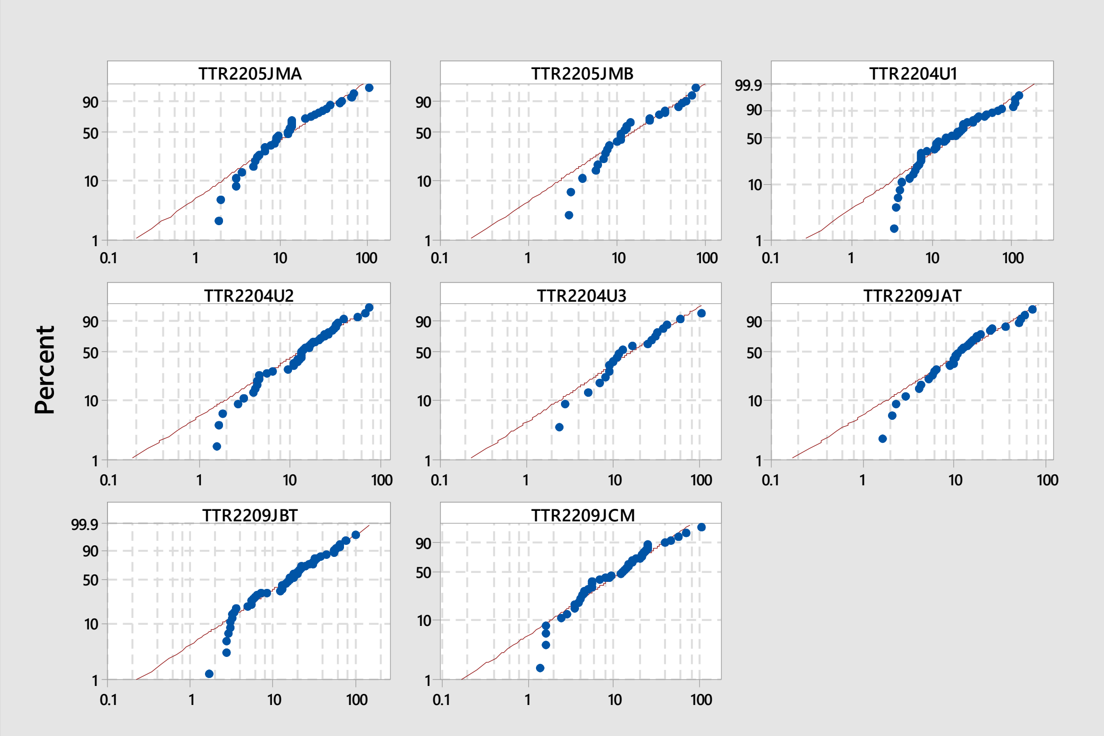

Fig. 4 Probability plot of TTR cooling tower

TABLE I
THE ANDERSON-DARLING STATISTICS OF TBT AND TTR

Equipment	Anderson-Darling Statistics		Scale Parameter (β)	
	TBF	TTR	MTBF	MTTR
2205-JMA	0.728	1.056	662.251	21.013
2205-JMB	0.855	1.204	834.028	21.463
2204-U1	0.747	1.260	502.260	26.766
2204-U2	1.014	1.080	538.503	18.556
2204-U3	1.227	1.048	1152.07	22.153
2209-JAT	0.965	1.030	686.341	16.897
2209-JBT	0.858	0.797	445.831	22.168
2209-JCM	0.779	0.882	549.149	16.249

From Fig. 3–4, it can be stated that constant failure and repair rates are acceptable. Further, Table 2 shows both the failure rate and repair rate of all equipment. The result will determine the criticality rating of equipment on reliability and availability analysis.

TABLE II
FAILURE RATE AND REPAIR RATE OF COOLING TOWER

Equipment	*Failure Rate (λ)*	*Repair Rate (r)*	*Status*
2205-JA	0.001510	0.04759	Online
2205-JB	0.001199	0.04659	Online
2204-U1	0.001991	0.03736	Online
2204-U2	0.001857	0.05389	Online
2204-U3	0.000868	0.04514	Standby
2209-JAT	0.001457	0.05918	Online
2209-JBT	0.002243	0.04511	Standby
2209-JCM	0.001821	0.06154	Online

The cooling tower system is dominated by a three-equipment system (one redundant unit and two operating units). Table 3 summarizes the overall reliability of all equipment. With a failure rate of 0.0008687/hour, 2204-U3 has the highest MTBF (1151,13 hours). It has been shown that both 2209-JBT and 2204-U1 have lower reliability and MTBF than other equipment. Fig. 5 represents the reliability of the equipment in units of time (hours). 2209-JBT and 2204-U1 show the lowest reliability value. However, in operating conditions, both 205JBT and 204-U1 are standby units. Under operating conditions, 2209-JAT and 2209-JCM operate to circulate cooled water to the urea and ammonia plant, while 205-JBT works for the standby unit. For induced draft fan (2204-U), 2204-U1 works for standby unit in normal operating conditions.

Both 2209 JAT and 2209 JCM, with MTTR of around 16 hours, show the best maintainability on a cooling tower system. Fig. 6 shows that 2209 JAT and JCM indicate acceptable maintainability results. Different results were found at 2204-U1, and that equipment shows the highest MTTR status. With a repair rate of 0.03736/hour, maintainability 2204 U1 shows poor maintainability and MTTR (represented by the red line). Induced draft fan 2204-U1 has an MTTR of 26.7608.

The Pareto chart in Fig. 7 shows the equipment components that are most responsible for any failures on 2205-JMA and 2205-JMB. Driven units, i.e., pumps, dominate most equipment causes. Seal or gland packing is a major problem in many pump failures (2205-JMA and 2205-JMB). Seal leaks will be considered a safety problem in some plant cases when dealing with dangerous fluids (e.g., liquid ammonia, toxic gas, or hot fluid). However, pump fluid is clean water in this case study, so seal damage or leakage is not a major safety problem.

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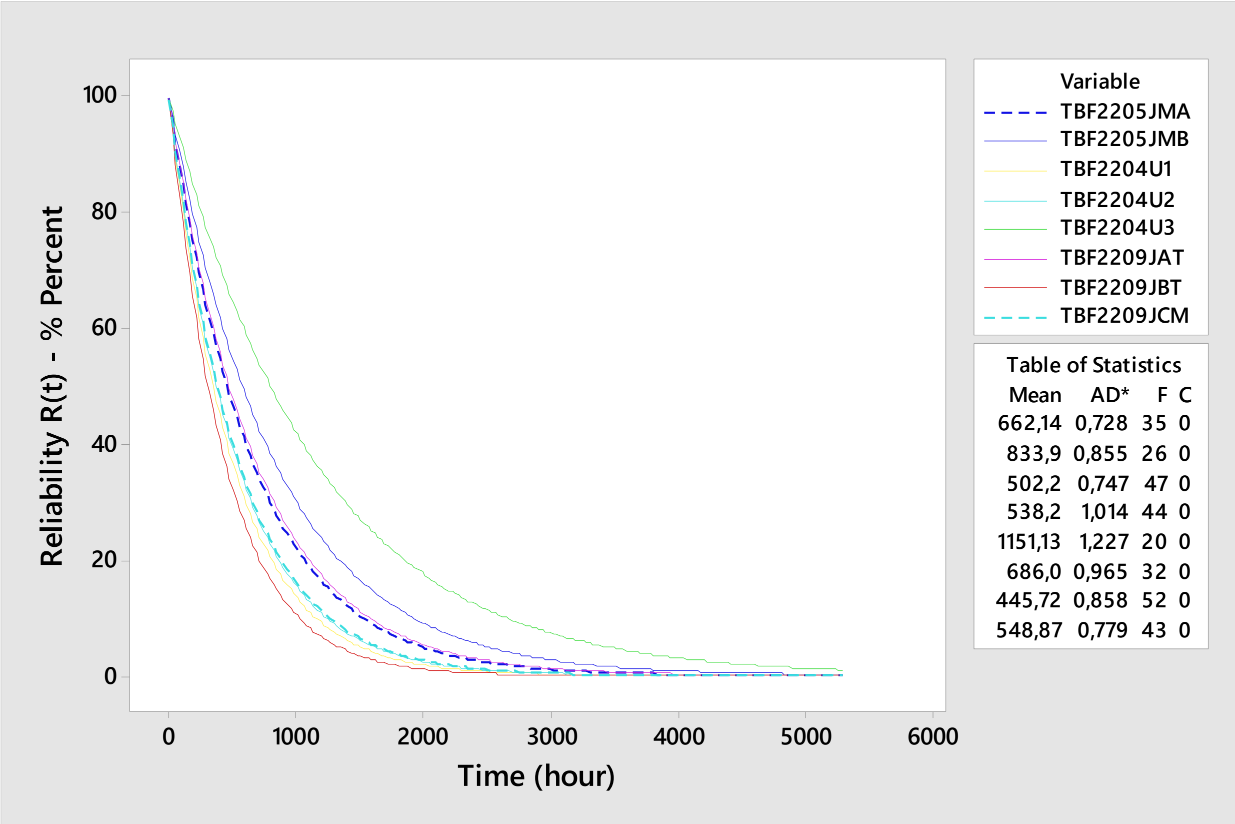

Fig. 5 Reliability diagram (survival plot) of cooling tower

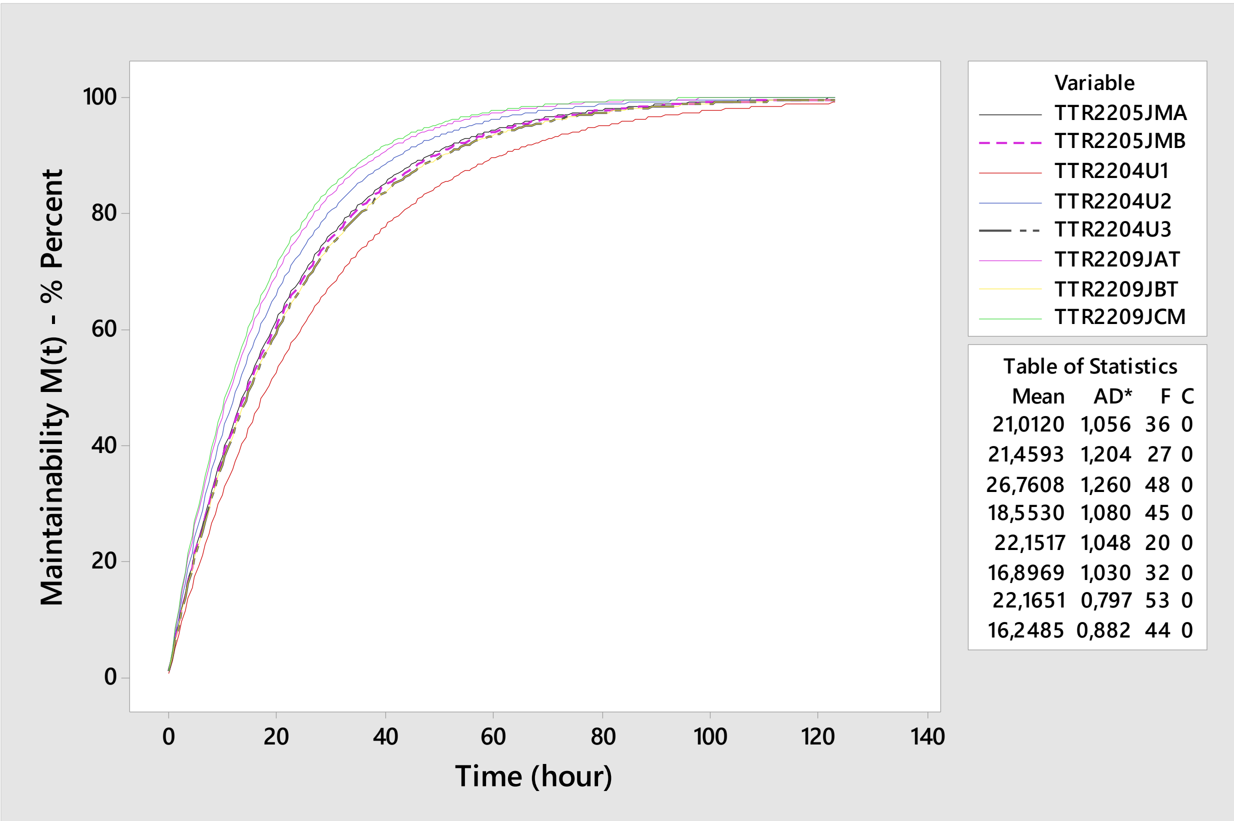

Fig. 6 Maintainability diagram of cooling tower

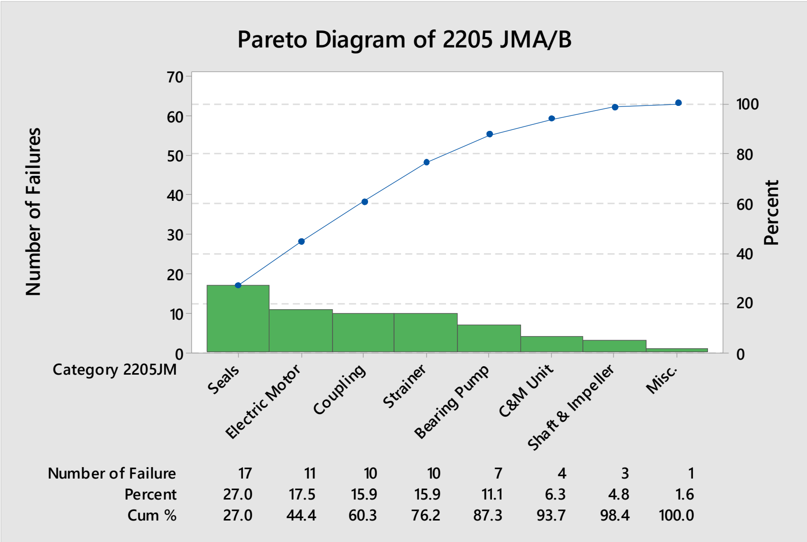

Fig. 7 Pareto chart for component failures of 2205-JMA and 2205-JMB

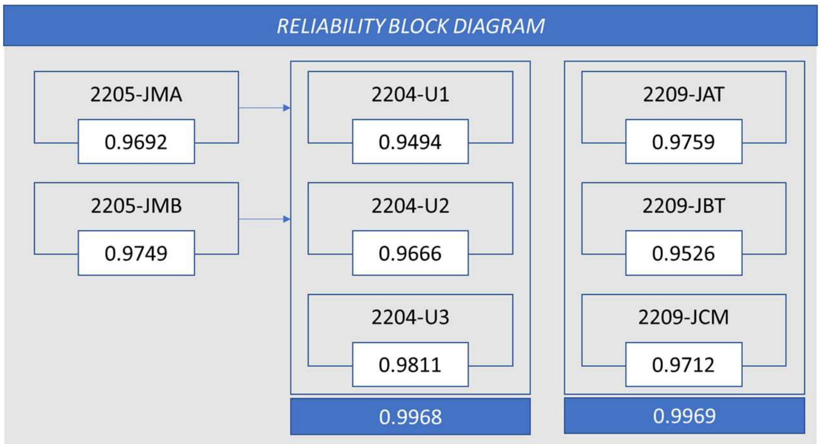

Fig. 8 Block diagram and availability of cooling tower

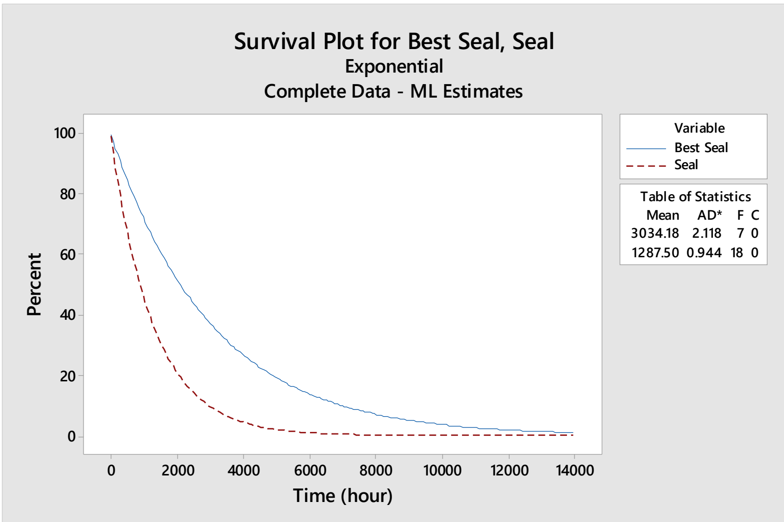

Fig. 9 Prediction of seal performance after upgrading

B. Evaluating The System Performance

Fig. 8 shows the block diagram, including the availability of the entire line of the cooling tower. Operational availability is determined by equipment that has a redundant or standby unit under normal operating conditions. Assuming that the failure rate and repair rate are constant, the system availability of the cooling tower is 0.9391 or 93.91 %.

Through availability analysis, both 0.996892 and 0.996997 are the availability of 2204-U induced draft fan and

Circulation CW Pump 2209-J, respectively. It shows that the equipment has high availability (higher than 99%). For equipment without a redundant unit, i.e., 2205-JMA and 2205-JMB, both operational availability are 0.9749 and 0.9692. Table 3 summarizes the reliability and availability of the cooling tower. Thus, 2205-JMA and 2205-JMB are considered the equipment with the lowest availability.

TABLE III
RAM CALCULATION OF COOLING TOWER

Equipment	Reliability R(t)	Maintainability R (t)	Availability
2205-JMA	$e^{-0,00151025t}$	$1- e^{-0.04759t}$	0.974913
2205-JMB	$e^{-0,00119911t}$	$1- e^{-0,04659t}$	0.969242
2204-U1	$e^{-0,0019910t}$	$1- e^{-0,03736t}$	0.996892
2204-U2	$e^{-0,00185773t}$	$1- e^{-0,05389t}$	
2204-U3	$e^{-0,0008687t}$	$1- e^{-0,04514t}$	
2209-JAT	$e^{-0,0014576t}$	$1- e^{-0.05918t}$	
2209-JBT	$e^{-0,0022435t}$	$1- e^{-0.04511t}$	0.996997
2209-JCM	$e^{-0,0018219t}$	$1- e^{-0.06154t}$	

Overall, a redundant system in the operating state can increase availability. With a redundant unit at 2204-U and 2209-J, the availability of cooling towers can operate up to 93.91%. It has been shown that redundant systems can increase system availability. Both 2204U1 and 2209JBT are standby units; operational availability is determined by considering online and standby units. It has been found that 2205-JMA and 2205-JMB equipment became critical equipment that had to be a maintenance concern. Cooling tower system failure will occur when one of the two pumps fails.

C. Discussion of Results

In the case of a cooling tower plant, pump units generally use packing seals in operation. Some advantages that should be considered when installing packing seals (compared to mechanical seals) include simple maintenance, easy installation and repairment (no special skills required), and low maintenance costs.

In general, pump performance depends on seal performance. Based on the theory, the seal is the weakest component of the pump. So, improvements in individual performance such as seals, roller bearings, and couplings significantly impact pump performance.

Leakage of packing seals not only results in product loss but also it is caused premature failure of the bearing. Experience shows that MTBF pumps are directly related to sealing reliability, and it summarizes that the improvement in reliability of the pump can be solely performed by increasing the reliability of the seal as the weakest component. It is known that the mechanical seal and packing seal MTBF is the lowest of all pump components. As well, it is confirmed that seals are the pump components that are the most vulnerable to the process conditions.

Most operating conditions where seals become bad actors have resulted from the inaccurate specification of process conditions. Therefore, examination of instrumentation measuring pressure, temperature etc., is strongly emphasized to avoid any deviation in the operating state. Even if it is only a very small deviation from the pressure gauge, it will result in incorrect readings and action from the operator.

Further, material upgrading can be carried out for handling pump failures due to packing seal damage. Based on visual examination, it has been found that softened packing seals g due to fluctuating process conditions. Some causes are the fluctuating pH of clean water, incompatibility of packing seals with fluid, or chemical attack.

Improvement of pumps should be prioritized on upgrading material, i.e., packing seal. The materials with a wide pH range should be performed to improve pump performance. The minimum and maximum pH values can be tested at a chemical laboratory to ensure the pH range in the cooling tower. Then, the data can be used as beneficial information for material upgrading. Overall maintenance recommendations or actions can only be taken when both pumps are not operating.

In addition, pump failures are also dominated by couplings, strainers, and bearings. The problems of those components are related to each other. Coupling failure, coupling misalignment, and pump suction problems will reduce roller bearing life. Based on the best seal performance over the operating period indicated by the highest MTBF, the performance prediction is calculated. The results achieved with these improvements amounted to 95.67 %. Fig. 9 shows the prediction of seal performance after upgrading.

System performance (cooling tower) results in a system availability of 93.91%. There is room for a system performance improvement of 6.09% that be carried out on critical subsystems. The maintenance action of critical subsystems will solely focus on the weakest components. The cooling tower index of RAM revealed that the values of reliability, availability, maintainability, and dependability parameters for the 2205-JMA and 2205-JMB subsystems were the lowest. MTTR values of 2205 JMA and 2205-JMB are relatively high than other online and redundant units.

Through RAM analysis, it has been shown that 2205-JMA and 2205-JMB (make-up pump) subsystem is the most critical equipment, and those pumps are important in the overall subsystem effectiveness. To increase system performance, major attention should be a focus on increasing the most critical equipment, i.e., make-up pump 2205-JMA and 2205-JMB.

In carrying out this research, there were several limitations, namely:

- That the rate of failure and repair is constant over a defined period of time.
- Equipment or subsystems may only have one of two conditions: a functioning condition or a failure condition.
- Repairs made to equipment result in the status of as-good-as-new (recovered as new).
- The process of switching from the online unit to the standby unit runs without problems.
- Failure and repair data are data in the last three years of the operational period

This research is limited to the assumption that the equipment or subsystem may only have one of two conditions, namely a functioning condition or a failure condition. However, in real conditions on the ground, this could be quite a few. The condition of equipment in the field is about functioning or failing and involves degradation of equipment function. Repair of equipment in the field may not result in as-good-as-new status (equipment can recover to its like-new condition). Repairs or corrective maintenance actions are often repeated for optimal results.

Based on Pareto charts and RAM analysis, Pump performance should be prioritized on critical components, i.e., packing seals or grand packing. Upgrading the packing seal material with a wide pH range can be conducted to improve pump performance. The prediction of the performance results achieved by upgrading is 95.6725%. As a result, the finding of this study on the cooling tower will be highly valuable to the cooling system. To achieve production targets, both departments of operation and maintenance should focus major attention and action on the most critical equipment.

IV. CONCLUSION

The result of the identification of the critical component or parts of the cooling tower shows that the most important equipment, according to RAM analysis, is the 2205-JMA and 2205-JMB (make-up pump) subsystem. Those pumps are critical to the overall performance of the subsystem. The most important equipment, namely the make-up pumps 2205-JMA and 2205-JMB, should be prioritized to improve system efficiency.

Many pump failures are caused by a problem with the seal or gland packing (2205-JMA and 2205-JMB). Seal leaks may be considered a safety issue in some plants when working with hazardous fluids (e.g., liquid ammonia, toxic gas, or hot fluid). In evaluating the system performance, pump performance should be prioritized on essential components, such as packing seals or grand packing. Pump performance can be improved by upgrading the packing seal material to one that has a broad pH range. The performance results obtained by upgrading are predicted to be 95.6725 percent.

ACKNOWLEDGMENT

This research was supported by HIBAH PUTI Universitas Indonesia 2020.

REFERENCES

[1] P. Tsarouhas, "Reliability, availability and maintainability (RAM) analysis for wine packaging production line," *Int. J. Qual. Reliab. Manag.*, vol. 35, no. 3, pp. 821–842, 2018, doi: 10.1108/IJQRM-02-2017-0026.

[2] J. Wang, Q. Zhang, S. Yoon, and Y. Yu, "Reliability and availability analysis of a hybrid cooling system with water-side economizer in data center," *Build. Environ.*, vol. 148, pp. 405–416, Jan. 2019, doi: 10.1016/j.buildenv.2018.11.021.

[3] M. C. Eti, S. O. T. Ogaji, and S. D. Probert, "Integrating reliability, availability, maintainability and supportability with risk analysis for improved operation of the Afam thermal power-station," *Appl. Energy*, vol. 84, no. 2, pp. 202–221, Feb. 2007, doi: 10.1016/j.apenergy.2006.05.001.

[4] L. Barberá, A. Crespo, P. Viveros, and F. Kristjanpoller, "RAM analysis of mining process: A case study of a Copper Smelting Process in the field of mining, Chile," in *IFAC Proceedings Volumes (IFAC-PapersOnline)*, Jan. 2012, vol. 45, no. 31, pp. 217–222, doi: 10.3182/20121122-2-ES-4026.00002.

[5] H. Garg and S. P. Sharma, "Behavior analysis of synthesis unit in fertilizer plant," *Int. J. Qual. Reliab. Manag.*, vol. 29, no. 2, pp. 217–232, Jan. 2012, doi: 10.1108/02656711211199928.

[6] K. Fu, Y. Xu, W. Zhang, and J. Zhang, "Study on availability test procedure of two-unit same redundant system with exponentially distributed up and down times unit," in *Proceedings of 2012 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering, ICQR2MSE 2012*, 2012, pp. 269–273, doi: 10.1109/ICQR2MSE.2012.6246233.

[7] C. Ebeling, *An introduction to reliability and maintainability engineering*. Singapore, 2004.

[8] H. Soltanali, A. H. S. Garmabaki, A. Thaduri, A. Parida, U. Kumar, and A. Rohani, "Sustainable production process: An application of reliability, availability, and maintainability methodologies in automotive manufacturing," *Proc. Inst. Mech. Eng. Part O J. Risk Reliab.*, vol. 233, no. 4, pp. 682–697, Aug. 2019, doi: 10.1177/1748006X18818266.

[9] P. Tsarouhas, "Reliability, availability and maintainability analysis of a bag production industry based on the six sigma DMAIC approach," *Int. J. Lean Six Sigma*, vol. 12, no. 2, pp. 237–263, Mar. 2020, doi: 10.1108/IJLSS-09-2019-0101.

[10] A. J. Ritchie and J. Brouwer, "Design of fuel cell powered data centers for sufficient reliability and availability," *J. Power Sources*, vol. 384, pp. 196–206, Apr. 2018, doi: 10.1016/J.JPOWSOUR.2018.02.059.

[11] N. Kumar, D. Rogers, T. D. Burnett, E. Sullivan, and M. Gascon, "Reliability, Availability, Maintainability (RAM) for Wind Turbines," *Am. Soc. Mech. Eng. Power Div. POWER*, vol. 2, Sep. 2017, doi: 10.1115/POWER-ICOPE2017-3045.

[12] P. Tsarouhas, "Evaluation of reliability, availability and maintainability of a milk production line," *Int. J. Ind. Syst. Eng.*, vol. 31, no. 3, pp. 324–342, 2019, doi: 10.1504/IJISE.2019.098543.

[13] P. Tsarouhas, "Statistical analysis of failure data for estimating reliability, availability and maintainability of an automated croissant production line," *J. Qual. Maint. Eng.*, vol. 25, no. 3, pp. 452–475, Aug. 2019, doi: 10.1108/JQME-04-2018-0029.

[14] H. P. Jagtap, A. K. Bewoor, R. Kumar, M. H. Ahmadi, M. El Haj Assad, and M. Sharifpur, "RAM analysis and availability optimization of thermal power plant water circulation system using PSO," *Energy Reports*, vol. 7, pp. 1133–1153, Nov. 2021, doi: 10.1016/J.EGYR.2020.12.025.

[15] M. Szkoda, G. Kaczor, and M. Satora, "Methodology of Building the Strategy of Maintenance of Rail Vehicles with the Use of the Rams Analysis in the Area of Safety," *J. Konbin*, vol. 49, no. 2, pp. 219–244, Jun. 2019, doi: 10.2478/jok-2019-0033.

[16] S. Hidirov and H. Guler, "Reliability, availability and maintainability analyses for railway infrastructure management," *Struct. Infrastruct. Eng.*, vol. 15, no. 9, pp. 1221–1233, Sep. 2019, doi: 10.1080/15732479.2019.1615964.

[17] P. H. Tsarouhas, "Reliability, availability, and maintainability analysis of an industrial plant based on Six Sigma approach: a case study in plastic industry," *Handb. Reliab. Maintenance, Syst. Saf. through Math. Model.*, pp. 1–17, Jan. 2021, doi: 10.1016/B978-0-12-819582-6.00001-0.

[18] S. Ahmadi, S. Moosazadeh, M. Hajihassani, H. Moomivand, and M. M. Rajaei, "Reliability, availability and maintainability analysis of the conveyor system in mechanized tunneling," *Meas. J. Int. Meas. Confed.*, vol. 145, pp. 756–764, Oct. 2019, doi: 10.1016/j.measurement.2019.06.009.

[19] D. Choudhary, M. Tripathi, and R. Shankar, "Reliability, availability and maintainability analysis of a cement plant: a case study," *Int. J. Qual. Reliab. Manag.*, vol. 36, no. 3, pp. 298–313, Mar. 2019, doi: 10.1108/IJQRM-10-2017-0215.

[20] A. K. Agrawal, V. M. S. R. Murthy, and S. Chattopadhyaya, "Investigations into reliability, maintainability and availability of tunnel boring machine operating in mixed ground condition using Markov chains," *Eng. Fail. Anal.*, vol. 105, pp. 477–489, Nov. 2019, doi: 10.1016/j.engfailanal.2019.07.013.

[21] J. Barabady, "Reliability and maintainability analysis of crushing plants in Jajarm bauxite mine of Iran," *Proc. - Annu. Reliab. Maintainab. Symp.*, pp. 109–115, 2005, doi: 10.1109/RAMS.2005.1408347.

[22] P. Gao, L. Xie, and J. Pan, "Reliability and Availability Models of Belt Drive Systems Considering Failure Dependence," *Chinese J. Mech. Eng. 2019 321*, vol. 32, no. 1, pp. 1–12, Mar. 2019, doi: 10.1186/S10033-019-0342-X.

[23] A. Aggarwal, S. Kumar, and V. Singh, "Performance modeling of the skim milk powder production system of a dairy plant using RAMD analysis," *Int. J. Qual. Reliab. Manag.*, vol. 32, no. 2, pp. 167–181, Feb. 2015, doi: 10.1108/IJQRM-01-2014-0007.

[24] P. Tsarouhas, "Reliability, Availability, and Maintainability (RAM) Study of an Ice Cream Industry," *Appl. Sci. 2020, Vol. 10, Page 4265*, vol. 10, no. 12, p. 4265, Jun. 2020, doi: 10.3390/APP10124265.