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Effectiveness Analysis Of A Centrifugal Pump In The Wax Ester Preparation Process Of Fatty Alcohol Production Using Overall Equipment Effectiveness

Prasetyo, Khariul Anshar*, Alfian Mahendra
Industrial Engineering, Faculty of Engineering, Universitas Malikussaleh, Aceh, Indonesia.
*Corresponding Author: khariulanshar@unimal.ac.id

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ABSTRACT

The reliability of production machinery determines process continuity, operational efficiency, and product quality in the oleochemical industry, particularly in the wax ester preparation stage of fatty alcohol production. This study analyzes the effectiveness of a centrifugal pump in the wax ester preparation unit using Overall Equipment Effectiveness (OEE) and identifies the causes of low machine effectiveness using a fishbone diagram. Data were collected from machine operating records for August 2025–January 2026, including machine working time, planned and unplanned downtime, and production volume. The results show an average availability rate of 91.99%, a performance rate of 84.61%, and a quality rate of 100%, yielding an OEE of 77.83%, which is below the world-class standard of the Japan Institute of Plant Maintenance (JIPM) of 85%. Planned downtime (226 hours) reduces loading time and is not a direct cause of the low performance rate, whereas failure and repair time (310 hours) lowered availability in three of the six months. The fishbone analysis identified five main groups of causes, namely man, method, environment, material, and machine, with delayed fault handling, inappropriate maintenance scheduling, and machine condition deterioration as the prominent causes. The study recommends strengthening preventive maintenance and checking component service life to improve the reliability of centrifugal pumps in fatty alcohol production.

Keywords: Centrifugal Pump, Fatty Alcohol, Fishbone Diagram, Maintenance, Overall Equipment Effectiveness.

1. Introduction

Production machine effectiveness is one of the factors that determine process continuity, operational efficiency, and product quality consistency in continuous-process industries, including the oleochemical industry. Equipment disruptions not only reduce output volume but also waste time, energy, and raw materials and raise overall production costs. This situation calls for a comprehensive method of measuring machine performance, one of which is Overall Equipment Effectiveness (OEE). OEE measures equipment effectiveness through three main dimensions, namely availability, performance, and quality, and identifies the main sources of production losses that occur during the process [1], [2].

Centrifugal pumps play a strategic role in the wax ester preparation process of fatty alcohol production because they transfer raw materials, intermediate products, and final products between unit operations. Because the process depends on the stability of pump performance, any decline in pump effectiveness can disrupt the overall flow of material. At the oleochemical company studied here, the

failure of centrifugal pump 110G2 on vessel 110D2 obstructed material flow in the wax ester preparation vessels, so operators diverted the flow from vessel 110D1 directly to vessel 110D3 (bypass), with additional alcohol and temperature adjustment. The disruption caused unplanned downtime of approximately 5–6 hours and required approximately 3–5 hours of operational recovery. It is reflected in monthly availability that fluctuated between 80.52% and 100%, and it may reduce the performance rate because the machine does not run at its ideal production speed.

Studies on OEE have expanded across many manufacturing sectors, from the automotive industry and vegetable oil processing [3] to precision manufacturing such as tool and die shops and [4] the pharmaceutical industry [5]. Recent work shows that OEE is no longer used merely as a historical indicator; it is also positioned as a strategic performance indicator within smart manufacturing based on digital monitoring [5]and integrated with continuous improvement approaches such as Kaizen to reduce various forms of production loss [6]. Increasingly dynamic production requirements have also led to extensions of the OEE concept that treat equipment flexibility as an additional dimension of effectiveness measurement [7]. Nevertheless, applications of OEE focused specifically on centrifugal pumps in the oleochemical industry remain relatively rare in the literature, leaving room for further study in this [8] context.

In line with the development of effectiveness measurement methods, maintenance strategies have also changed [9] significantly. Total Productive Maintenance (TPM) has been shown to improve production efficiency in various process industries, including crude oil processing [9] and the packaging of chemical products for the agroindustry sector [10]. This transformation is reinforced by predictive maintenance based on Industry 4.0 technology, which enables equipment failures to be anticipated through continuous condition monitoring before damage occurs [11]. The shift from corrective to predictive maintenance has also been reported to reduce failure costs significantly, particularly in continuous-process industries [12].

At a more specific level, several studies have examined the reliability of centrifugal pumps and pumping systems in various process-industry contexts. A case study on a motor pump showed that an appropriate maintenance strategy can improve reliability and reduce operating costs simultaneously [13]. Reliability-centered maintenance (RCM) applied to centrifugal pumps has also been shown to yield more economical maintenance strategies than conventional approaches [14]. An RCM study of a cooling water pump in the fertilizer industry found that aging machines caused high downtime and called for priority on critical components [15]. The use of smart sensors for monitoring and predictive maintenance of centrifugal pumps has been increasingly adopted in recent years [16]. This development is reinforced by reliability and risk-centered maintenance, which integrates risk into maintenance planning more comprehensively [17], and by a reliability study of a multistage pumping system that emphasized evaluating historical failure data to determine optimal maintenance intervals [18]. The choice of maintenance strategy must consider differing operating conditions, because no single strategy is universally optimal for all types of equipment and operating conditions [12].

To trace the root causes of low machine effectiveness systematically, the fishbone (cause-and-effect) diagram is widely used as an analytical tool that organizes possible causes into five main factors: man, method, environment, material, and machine. This approach has proven relevant in various contexts, from management decision-making [19] and process quality improvement [20]to analyzing the causes of high losses in machines at a palm oil mill [21].

Based on the above, the decline in centrifugal pump effectiveness in the wax ester preparation process cannot be understood adequately through observation of operational symptoms alone. It requires structured measurement through OEE and systematic root-cause analysis through a fishbone diagram. Combining the two approaches is expected to provide a comprehensive picture of pump effectiveness and the factors that influence it, so that the company can formulate more effective maintenance strategies to support the reliability of oleochemical plant operations. This study aims (1) to calculate the availability, performance rate, quality rate, and OEE of the centrifugal pump in the wax

ester preparation unit for August 2025–January 2026, and (2) to identify the factors that cause its low effectiveness.

2. Method

2.1 Research Design and Location

This study uses a case study approach with a descriptive quantitative design to describe pump effectiveness in measurable terms based on actual operating data. The study was conducted at an oleochemical company in the Kuala Tanjung industrial area, Batubara Regency, North Sumatra, Indonesia. The object of observation was centrifugal pump 110G2 in the wax ester preparation unit of the Fatty Alcohol Department. Field observation lasted one month (January 19–February 19, 2026), whereas the machine performance data analyzed cover August 2025 to January 2026, to obtain a representative picture of performance that is not limited to momentary conditions.

2.2 Data and Data Collection Techniques

The data consist of historical pump performance data and field observation data. The historical data for August 2025–January 2026 (six months) were obtained from the company's operational records and cover machine working time, planned downtime, set-up and adjustment time, failure and repair time, production volume, and the volume of rejected or reworked products. These data were taken from existing records and were not generated through direct observation. Data consistency was verified by recalculating the relationships among the time components in each month, namely that loading time equals machine working time minus planned downtime, and that operation time equals loading time minus set-up and adjustment time and failure and repair time, and by checking monthly values against period totals. Field data collected over one month consisted of direct observation, documentation, and interviews and discussions with operational and maintenance personnel; they were used to understand pump operating conditions and to construct the fishbone diagram. Company profile and organizational structure documents served as supporting context for understanding the operating system.

2.3 Data Analysis Techniques

Data were analyzed using Overall Equipment Effectiveness (OEE), which measures machine effectiveness through three main components: availability, performance rate, and quality rate [1], [2]. Overall OEE is obtained by multiplying the three components, as given in the following equation.

$$\text{OEE} = \text{Availability} \times \text{Performance Rate} \times \text{Quality Rate} \times 100\% \quad (1)$$

Availability describes the proportion of actual operating time to planned operating time and is calculated from loading time and operation time, as given in Equations (2) to (4). All times are expressed in hours. Because planned downtime is removed in Equation (3), it affects only loading time, whereas set-up and adjustment time and failure and repair time reduce operation time in Equation (4).

$$\text{Availability} = (\text{Loading Time} - \text{Downtime}) / \text{Loading Time} \times 100\% \quad (2)$$

$$\text{Loading Time} = \text{Machine Working Time} - \text{Planned Downtime} \quad (3)$$

$$\text{Operation Time} = \text{Loading Time} - \text{Set Up and Adjustment} - \text{Failure and Repair} \quad (4)$$

The performance rate describes how closely the machine reaches its ideal production speed relative to actual conditions. The ideal cycle time (ICT) is the processing time per cubic meter at the ideal rate. In this study, ICT was derived from the design capacity of the unit and the density of the process stream.

The design capacity of Section 110 is 120 tons/day (5.0 tons/h), and the process-stream density was assumed to be 0.70 tons/m³, giving an ideal flow rate of 5.0 / 0.70 = 7.14 m³/h. ICT follows from Equation (5), with consistent units: (tons/m³) / (tons/h) = h/m³. The same ICT was applied to all months.

$$\text{Ideal Cycle Time (h/m}^3\text{)} = \text{Density} / \text{Design Capacity} = 0.70 / 5.0 = 0.14 \quad (5)$$

$$\text{Performance Rate} = (\text{Production Volume} \times \text{Ideal Cycle Time}) / \text{Operation Time} \times 100\% \quad (6)$$

With production volume in m³, ICT in h/m³, and operation time in hours, the performance rate is dimensionless.

The quality rate describes the proportion of products that meet quality standards relative to total production, as given in Equation (7).

$$\text{Quality Rate} = (\text{Production Volume} - \text{Reject and Rework}) / \text{Production Volume} \times 100\% \quad (7)$$

Period values were calculated as the arithmetic mean of the monthly values. The OEE results were interpreted against the world-class standards set by the Japan Institute of Plant Maintenance (JIPM), namely availability of 90%, performance of 95%, quality of 99%, and overall OEE of 85% [1]. An OEE below this threshold indicates production losses that require further investigation, which was organized using the six big losses framework [22].

2.4 Root Cause Analysis.

To identify the factors that cause the low effectiveness of the pump, this study used a fishbone diagram as a cause-and-effect analysis tool. The diagram is organized into five factor categories, namely man, method, environment, material, and machine, each of which is examined to obtain a systematic picture of root causes [19]–[21]. The causal factors were compiled from field observation and documentation of pump conditions and were then confirmed through interviews and discussions with operational and maintenance personnel in the wax ester preparation unit, so that the identified factors reflect actual conditions rather than theoretical assumptions.

3. Results and Discussion

3.1 Machine Performance Data

The performance data of the centrifugal pump in the wax ester preparation unit for August 2025–January 2026, used as the basis for the OEE calculation, are presented in Table 1.

Table 1. Centrifugal Pump Performance Data, August 2025–January 2026

Month	Machine Working Time (h)	Planned Downtime (h)	Failure and Repair (h)	Production Volume (m³)
August	696	80	120	3,127.9
September	744	0	0	4,284.3
October	720	0	0	4,287.4
November	744	98	115	3,245.9
December	720	0	0	4,284.8
January	744	48	75	3,836.9

No set-up and adjustment time and no rejected or reworked products were recorded during the observation period.

3.2 Calculation of Availability, Performance, and Quality Rates

Availability was calculated from loading time and operation time for each month using Equations (2)– (4). For example, in August the loading time was 616 hours (696 hours minus 80 hours of planned downtime) and the operation time was 496 hours (616 hours minus 120 hours of failure and repair), giving an availability of 496/616 × 100% = 80.52%. The availability values for all months are summarized in Table 2.

Table 2. Summary of Availability Rate

Month	Loading Time (h)	Operation Time (h)	Availability Rate (%)
August	616	496	80.52
September	744	744	100.00
October	720	720	100.00
November	646	531	82.20
December	720	720	100.00
January	696	621	89.22
Average			**91.99**

Average availability exceeds the JIPM standard (90%), but the three months with failure and repair time (August, November, and January) fall below it.

The ICT of 0.14 h/m³ (Equation 5) was used to calculate the monthly performance rate with Equation (6). For example, in August the performance rate = (3,127.9 × 0.14)/496 × 100% = 88.29%. The performance rates are summarized in Table 3.

Table 3. Summary of Performance Rate

Month	Operation Time (h)	Production Volume (m³)	Performance Rate (%)
August	496	3,127.9	88.29
September	744	4,284.3	80.62
October	720	4,287.4	83.37
November	531	3,245.9	85.58
December	720	4,284.8	83.32
January	621	3,836.9	86.50
Average			**84.61**

No rejected or reworked products were found in any month, so the quality rate based on Equation (7) was a consistent 100% each month.

3.3 Overall Equipment Effectiveness

Using the average availability, performance rate, and quality rate, the OEE of the centrifugal pump from Equation (1) is:

OEE = 91,99% × 84,61% × 100% = 77,83%

Table 4. Summary of Centrifugal Pump OEE

OEE Factor	Value (%)	JIPM World-Class Standard (%)
Availability	91.99	90
Performance Rate	84.61	95
Quality Rate	100	99
OEE	77.83	85

The OEE of 77.83% is below the JIPM world-class standard of 85% [1]. The component with the largest gap to the standard is the performance rate (84.61% versus 95%), which is the main critical point

for improving machine effectiveness. Planned downtime of 226 hours reduced loading time from 4,368 to 4,142 hours and did not directly lower the performance rate, whereas failure and repair time of 310 hours reduced operation time to 3,832 hours and lowered availability. The months without any downtime (September, October, and December) actually had the lowest performance rates (80.62–83.37%), so the low performance rate is associated with the pump's operating rate rather than with the length of planned downtime.

3.4 Root Cause Analysis (Fishbone)

To trace the causes of the pump's low effectiveness, a fishbone analysis was carried out across the five factor categories, using the identification and confirmation procedure described in Section 2.4. The results are presented in Table 5.

Table 5. Fishbone Analysis of the Causes of Low Machine Effectiveness

Factor	Causes	Solutions
Man	Personnel are not prompt in responding to machine disturbances; low operator carefulness; insufficient operator staffing	Operator training and recruitment of competent personnel
Method	Inappropriate maintenance scheduling; maintenance not carried out immediately after a disturbance; insufficient attention to SOPs	Preventive maintenance scheduling based on historical data and stronger SOP supervision
Environment	Sea wind and humidity cause corrosion; high noise makes abnormal sounds hard to detect	Corrosion protection and periodic inspection; hearing protection and sensor-based condition monitoring
Material	Material quality does not meet specifications and non-original brands are used; unsuitable lubricant	Quality testing of materials before use and use of manufacturer-recommended lubricant
Machine	Insufficient maintenance and repeated failures; bearing wear and lubrication system problems	Routine component inspection and monitoring of lubricant pressure and flow

This kind of cause-and-effect analysis has proven effective for tracing root causes systematically, both in managerial decision-making [19] and in production quality improvement [20].

The OEE of 77.83% indicates that the centrifugal pump in the wax ester preparation unit still has considerable room for improvement before reaching the world-class standard. OEE studies in the vegetable oil [3] and pharmaceutical [5] industries likewise use the metric to expose gaps against world-class standards, and the low performance rate observed here may reflect a broader tendency in continuous-process industries, where operating speed is easily reduced by recurring small obstructions.

Conceptually, production losses can be traced using the six big losses framework, which groups losses into those related to availability, speed, and quality [22]. For pump 110G2, the failure and repair time of 310 hours (120 hours in August, 115 in November, and 75 in January) falls under breakdown losses that lower availability, equivalent to 7.5% of loading time. During these disturbances, flow was diverted through the 110D1-to-110D3 bypass with additional alcohol and temperature adjustment, and recovery took about 3–5 hours before the process returned to normal. The process did not run at its ideal rate during this adjustment, which constitutes a reduced-speed loss. Planned downtime (226 hours, or 5.2% of machine working time) is not a loss that lowers the performance rate, because it has already been removed from loading time in Equation (3). The data are also inconsistent with a direct link: months without downtime had an average performance rate of 82.44%, lower than months with planned downtime (86.79%). Because the performance rate scales linearly with ICT, this ordering holds

regardless of the ICT value used. It confirms that the pump's operating rate, not the length of planned downtime, is the main source of the low performance rate.

The root causes of low pump effectiveness can be traced further through the fishbone analysis, which links the man, method, environment, material, and machine factors. Causes under machine and material, namely bearing wear, insufficient maintenance, and unsuitable lubricant and material, explain the breakdown losses of the pump and agree with an RCM study of a pump in the fertilizer industry that identified lubrication components as critical [15]. Under method, inappropriate maintenance scheduling and maintenance that is not carried out immediately, together with the lack of promptness under man, relate to the length of failure and repair time and the recovery period after the bypass. These findings are also consistent with a motor pump reliability study showing that a well-targeted maintenance strategy improves reliability while reducing operating costs [13], and with the application of RCM to centrifugal pumps, which yielded more economical maintenance strategies [14]. The same five-factor structure has also been used to analyze machine losses at a palm oil mill [21].

The shift from reactive to predictive maintenance is also relevant, since it has been reported to reduce failure costs significantly in continuous-process industries [12]. Smart sensors for real-time condition monitoring of centrifugal pumps [16] may be a relevant next step, particularly for detecting early signs of bearing wear identified under the machine factor in the fishbone analysis, and for compensating for environmental noise that makes manual detection difficult.

In practice, these findings imply that efforts to improve pump effectiveness should focus on strengthening preventive maintenance based on historical data [18], standardizing material and lubricant quality, handling disturbances more quickly, and supervising compliance with operating SOPs. The process flow arrangement, including a more effective bypass line, also deserves evaluation to reduce the impact of failures of pump 110G2. The coastal location of the oleochemical plant is a further consideration, because exposure to sea air may accelerate corrosion of critical pump components.

This study has limitations. The observation period is relatively short (six months) and covers a single centrifugal pump, so generalization to other equipment should be made with caution. The performance rate also depends directly on the ICT, which was derived from the design capacity and an assumed process-stream density of 0.70 tons/m³. Using the same capacity, densities of 0.75 and 0.80 tons/m³ would give ICT values of 0.15 and 0.16 h/m³, average performance rates of 90.65% and 96.70%, and OEE values of 83.39% and 88.95%, respectively. The availability results and the decomposition of losses do not depend on ICT, but conclusions about the absolute performance level require validated density data for the process stream. Future studies should cover more equipment in the production line, use longer observation periods, and quantify the contribution of each loss category.

4. Conclusion

The OEE of the centrifugal pump in the wax ester preparation unit is 77.83%, below the JIPM world-class standard of 85%, based on an availability rate of 91.99%, a performance rate of 84.61%, and a quality rate of 100%. The low OEE is mainly due to a performance rate that has not yet been optimal, whereas availability declined in the three months with failure and repair time, totaling 310 hours, which reduced operation time to 3,832 hours from a loading time of 4,142 hours. Planned downtime of 226 hours reduced loading time and is not a direct cause of the low performance rate. The fishbone analysis identified five main causal factors, namely man, method, environment, material, and machine, with inadequate maintenance methods as a significant contributor to the decline in machine effectiveness. These findings confirm that improving pump effectiveness cannot be done in a piecemeal way. It requires comprehensive improvement in maintenance scheduling, fault handling, material quality, operator competence, and control of the working environment at the same time.

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Declaration of AI Use

The author states that ChatGPT was used to a limited extent to assist with language editing and grammar checking during the preparation of the manuscript. The author bears full responsibility for all scientific content, data analysis, interpretation of results, and conclusions. All editing assisted by ChatGPT has been reviewed and verified by the author.

Author Contributions

Conceptualization, Khariul Anshar, and Alfian Mahendra; methodology, Khariul Anshar; formal analysis, Khariul Anshar, and Prasetyo; investigation, Khariul Anshar; data curation, Khariul Anshar; writing—original draft preparation, Khariul Anshar and Prasetyo; writing— review and editing, Alfian Mahendra. All authors have read and agreed to the published version of the manuscript.

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