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JOURNAL INDUSTRIAL SERVICESS
journal homepage: http://jurnal.untirta.ac.id/index.php/jiss
eISSN 2461-0631

Original research article

Optimizing centrifugal water pump design for enhanced water use efficiency in Batam Marina Plantations

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ARTICLE INFO

Article history:
Received 20 June 2024
Received in revised form 19 February 2025
Accepted 3 March 2025
Published online 23 March 2025

Keywords:
Centrifugal pump
Design for Manufacture and Assembly (DFMA)
Efficiency
Service life

Editor:
Bobby Kurniawan

Publisher's note:
The publisher remains neutral concerning jurisdictional claims in published maps and institutional affiliations.

ABSTRACT

Water demand in the plantation area has been increasing by 6% per year due to population growth, making the existing main water pump insufficient. To address this, a new centrifugal pump was designed with a focus on efficiency and ease of assembly using the Design for Manufacture and Assembly (DFMA) method and the French design analysis method. This study aims to develop an optimal pump design with an estimated service life of over five years, ensuring a reliable and sustainable water supply for the plantation area. The DFMA analysis showed that the design efficiency index improved from 0.30% in the current design to 0.77% in the alternative design—an increase of 0.47%. The alternative design was chosen because it offers faster assembly, lower costs, and fewer components compared to the existing model. Beyond improving efficiency, the optimized centrifugal pump is expected to last more than five years. This durability is supported by using corrosion-resistant grade 316 stainless steel for key components, material strength tests through finite element analysis (FEA) simulations under maximum operating conditions, and fatigue testing on the impeller, which confirmed its ability to withstand repeated use.

1. Introduction

Centrifugal pumps are the most commonly used type of dynamic pump due to their relatively low cost and simple design [1]. These pumps convert mechanical energy into hydraulic energy through centrifugal force to move fluids [2], [3]. The main components include the impeller, pump housing, motor, connecting shaft, and other supporting parts [4].

Inadequate water availability will certainly hinder activities in various aspects, such as providing clean water for plant irrigation, livestock needs, residential use, drinking water, and other utilities [5]. The use of centrifugal pumps has played a crucial role in the water distribution process, both in the main channels and downstream of the distribution network [6], [7]. Table 1 presents a record of data on water supply requirements in the Marina plantation area of Batam City.

Currently, many pump companies continue to develop their products by creating adaptive centrifugal pumps to meet the needs of distributing liquid and gaseous fluids [8]. Companies around Batam City offer unique advantages, including material types, self-priming features, and automatic on-off switches [9], [10]. Although uncommon, there are also custom pump orders designed for critical conditions, such as oil drilling areas or extreme temperatures [11], [12]. The main parameters for selecting a centrifugal pump are head and capacity [13]. During operation, the pump requires components such as pipes for fluid transfer, pressure gauges, and valves to regulate the flow [14], [15].

Table 1.
Water consumption of Batam Marina Plantation

No	Usage	Consumption (L/days)
1	Garden needs	111,375
2	Fishpond needs	108,000
3	Cattle needs	1,485
4	Goat livestock needs	375
5	Home needs	22,752
6	Mushola needs	3,555
Total		247,542

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http://dx.doi.org/10.62870/jiss.v11i1.26485

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At the Batam Marina Plantation, water plays a vital role in supporting plantation activities and livestock. However, water demand continues to increase by approximately 6% annually due to population growth, leading to a decrease in pressure at the main pump, which cannot meet user demand [16]. Inadequate water availability will certainly hinder various activities, such as plant irrigation, animal husbandry, household needs, drinking water, and other utilities. The use of centrifugal pumps is crucial in the water distribution process, both in the main channels and downstream distribution. In efforts to replace a pump to meet water supply needs, pump capacity and head are the primary considerations, as higher capacity results in higher costs and operational expenses. Regarding the issue at the Marina Plantation, where the centrifugal pump cannot meet the demand for clean water, researchers are interested in designing a new centrifugal pump with an estimated service life of over 5 years.

The addition of new design methods, such as Quality Function Deployment (QFD) and Design for Six Sigma (DFSS), can strengthen this research [17]. QFD helps translate the water use efficiency needs of the Batam Marina plantation into measurable pump technical specifications and sets targets based on priorities [18]. Meanwhile, DFSS provides a statistical approach for design optimization to achieve Six Sigma quality, predict pump performance, and identify potential failures that need to be eliminated during the design stage [19].

The method used is DFMA (Design for Manufacturing and Assembly) to reduce assembly costs of supporting elements and piping, as well as the French analysis design method to analyze and validate alternative centrifugal pump designs [6], [20]. In designing centrifugal pumps, the DFMA approach can be applied to optimize the manufacturing and assembly processes of pump components [21]. This approach aims to minimize production costs, improve quality, and reduce assembly time [22].

The selection of DFMA and French Analysis in this study is highly appropriate for several reasons [23]. DFMA is particularly relevant since centrifugal pumps are manufactured products requiring component assembly. This method optimizes the design for easier production while reducing manufacturing costs [24]. Meanwhile, French Analysis provides a systematic approach to analyzing product functions, identifying the primary and supporting functions of centrifugal pumps, and evaluating the cost-effectiveness of each function [25]. The combination of these two methods strikes a balance between manufacturing optimization and comprehensive functional analysis, ultimately enhancing water use efficiency [26].

This research contributes by integrating manufacturing optimization techniques with functional water analysis methods, demonstrating how this novel approach enables precise identification of water inefficiencies while simultaneously providing practical optimization solutions for industrial processes [27], [28]. This synergistic approach addresses both the analytical and implementation aspects of improving water use efficiency, bridging a gap in existing research, which often focuses solely on either optimization or analysis in isolation [29], [30].

2. Material and method

2.1. Research variable

The variables used in this research are independent and dependent variables. The independent variable in this study is the water distribution installation system, while the dependent variable is the centrifugal pump package.

2.2. Data analysis

The data has been obtained from interviews and observations will be used as the basis for the design, therefore a step-by-step procedure is needed in analyzing the data as follows:

1. Determine the basic design parameters. At this stage, basic parameters will be determined through calculations using equations to produce data advanced planning.
2. Analysis and design of alternative French design methods. Based on the results of the parameters that have been determined, then the values. This will be used as a basis for determining geometry design according to requirement specifications.
3. DFMA analysis of existing designs. In this phase, component identification is carried out using the Bill of Material. Then the data obtained will be processed using. DFA analysis with the aim of knowing the estimated number of components, time and assembly costs, as parameters for calculating the design efficiency index.
4. DFMA analysis of alternative designs. At the DFA analysis stage in alternative designs there are initial steps incomponent selection based on design criteria references, The aim is to eliminate and substitute components which is not appropriate for existing conditions.
5. Analysis and design selection. After obtaining the design results which are determined based on the analysis French and DFMA, then a comparison of specifications and design efficiency index between existing and alternative designs. This matter carried out with the aim of obtaining more optimal design results

3. Results and discussions

3.1. Design parameters

The current situation indicates that the existing centrifugal pumps can no longer meet the required water flow demand. Therefore, before designing a new pump, the following basic parameters must first be determined. The design parameters are shown in Table 2.

Table 2.
Reference parameters for centrifugal pump design

Specification	Requirement
Fluid	Fresh Water
Saturated vapor pressure	0.0317 atm
Specific Gravity of Fluid	0.997
Fluid density	997 kg/m³
Fluid viscosity	0.000890 kg/m.s
Actual discharge capacity requirement	10,314 m³/h
Pump type	Sentrifugal Single Stage
Head pump	7 m – 13 m
Pump capacity	12 m³/h – 4 m³/h
Motor power	1.1 kW

Table 3.
Alternative centrifugal pump specifications

Specification	Requirement
Pump Capacity	13.32 m³/h
Total Pump Head (H)	19 m
Specific Speed (ηs)	14
Impeler Type	Radial Flow
Pump Efficiency (ηp)	78.6 %
Electric Motor Power	1 kW
Motor Speed (η)	3000

Table 4.
Impeler design

No.	Decription	Dimensions
1	Impeller Shaft Diameter (Ds)	14 mm
2	Impeller Neck Diameter (Dh)	20 mm
3	Impeller Eye Diameter (D0)	43 mm
4	Impeller Inlet Diameter (D1)	49 mm
5	Impeller Entrance Angle (β1)	23.39°
6	Lebar Sisi Masuk Impeller (b1)	10.96 mm
7	Impeller Exit Diameter (D2)	140 mm
8	Impeller Exit Angle (β2)	27°
9	Number of Impeller Vanes (z)	5

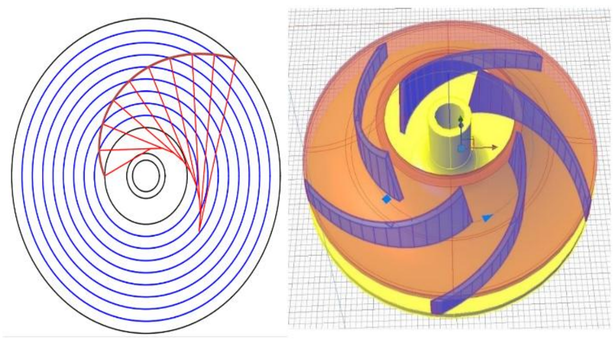

Figure 1. Impeller design

3.2. *Specifications result of centrifugal pump planning*

These specifications are based on calculations and technical considerations to meet the irrigation needs of the Marina Batam plantation. Based on the calculations, the specifications for the centrifugal pump in this plan are determined as shown in Table 3.

Table 5.
Volute dimension calculation

Φv (Deg)	Av (mm²)	rvi (mm)	Rv (mm)
0	0	0	75.60
90	125.55	6.32	81.92
135	188.32	7.74	84.34
180	251.09	8.94	86.54
225	313.86	10.00	88.60
270	376.64	10.95	90.55
315	439.41	11.83	92.43
360	502.18	12.65	94.25

3.3. *Impeler design*

To determine the geometry of the shaft and impeller for a centrifugal pump, a calculation is required. However, in this design, the calculation will be performed using the CPD (Centrifugal Pump Designer) application. Table 4 shows the input parameters for the CPD application. Fig. 1 shows the impeler design using parameters from Table 4.

3.4. *Impeler blade design*

After determining the main dimensions of the impeller, the next step is to draw its shape. In this depiction, the circular arc method is used by dividing the impeller into several concentric circles. Before proceeding to the drawing stage, the necessary values for defining the impeller geometry must first be calculated using Eq. (1).

$$R = \frac{{R_a}^2 - {R_b}^2}{2\,(R_b \cos\beta_b - R_a \cos\beta_a} \quad (1)$$

3.5. *Pump house design*

The type of pump housing used in this design is a volute spiral shaped. The reason why you choose a volute pump house is because of the type. This is very commonly used in single stage pumps and for larger constructions simply because it is made by printing. In this design, the volute is divided into 8 cross-sectional sections with angles 45°, 90°, 135°, 180°, 225°, 315° and 360°. Table 5 shows the volute dimension calculation.

3.6. *DFA analysis of existing design*

This DFA analysis stage will be carried out using Boothroyd G's design efficiency index calculation method. Additionally, slight modifications will be made to parts of the insertion code and handling code, based on considerations of labor cost suitability and assembly time at the planned location. The existing centrifugal pump design requires 104 components. In the current assembly process, only four types of operational activities are performed: fit-up material, weld joint, thread joint, and socket joint, making the analysis more straightforward. The results of the DFA analysis are shown in Table 6.

Table 6.
Result of existing DFA analysis

Assembly type	Number of assemblies	Operating time (second)	Operating cost	Percent use of time and cost
Fit up material	66	7,920	IDR 82,368	7.77 %
Weld joint	29	91,212	IDR 948,605	89.10%
Thread joint	220	2,640	IDR 27,456	2.95 %
Socket joint	9	180	IDR 1,872	0.18 %
Total	324	101,952	IDR 1,060,301	100%

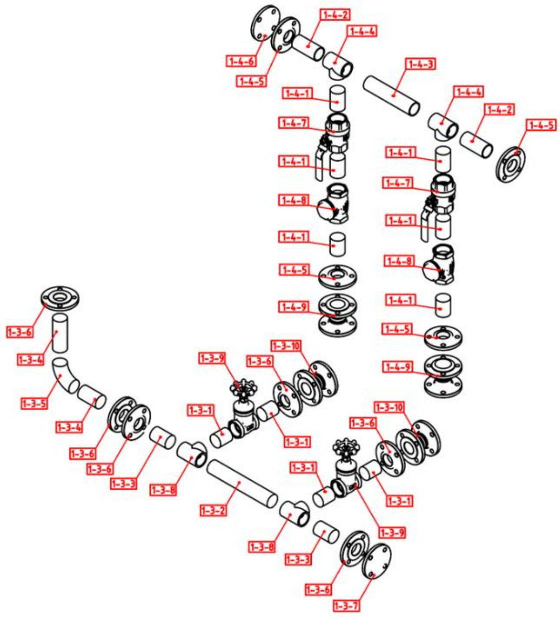

Figure 2. Explode view suction & discharge pump

In the DFA analysis, operating costs are calculated based on the average wage per worker for an 8-hour workday, which is IDR 300,000. The workers considered in this analysis have expertise in the previously mentioned field. Additionally, the duration of operation for each component is also considered.

3.7. Design improvements

Basically, improvements to the design of this centrifugal pump installation aim to meet the required water distribution capacity at the research location. However, even though the specifications for the centrifugal pumps have been determined, there are still several factors that must be considered. The analysis stage is carried out to obtain a valid design that meets the desired design criteria. Figure 2 is an exploded view of the components in the suction and discharge pump sections.

After determining the operating parameters of the pump specifications, the pipe components in the suction pump section are used to transport fluid from the tower tank outlet to the pump inlet. A total of 18 pipes are used, with an NPS of 2", made of galvanized carbon steel (ASTM A53 Grade A) with a thickness of 3.05 mm. To meet the design requirements, Schedule 40 was chosen, with a thickness of 3.91 mm. This ensures that the selected pipe meets the design criteria and that the components are readily available on the market.

The fitting components function as flow direction changes. There are two types of fittings—elbows and tees—totaling five components. The size and material specifications used for these components are equivalent to the results of the pipe analysis; therefore, no further analysis is required for specification selection.

Flange components are used as connectors between pipes and other components, such as fittings and valves. To meet the design criteria, the type of flange is determined based on the pressure and temperature under pump operating conditions. Below is the determination of flange specifications. With an input pressure parameter of 1.9 atm at a temperature of 25°C, a 2" flange rated at 150, made from A182 Gr. F53 material, was selected. These results confirm that the flange component has sufficient strength to withstand operating pressure and is readily available on the market.

There are three types of valves: gate valves, ball valves, and swing check valves. The special item component consists of four flexible joint components, which are directly connected to the pump inlet and outlet. These components function to reduce vibrations caused by motor rotation, which is transmitted to the shaft and impeller. They were specifically chosen to prevent leaks and damage to the threaded connections in other components, ensuring that the system's components have a longer lifespan.

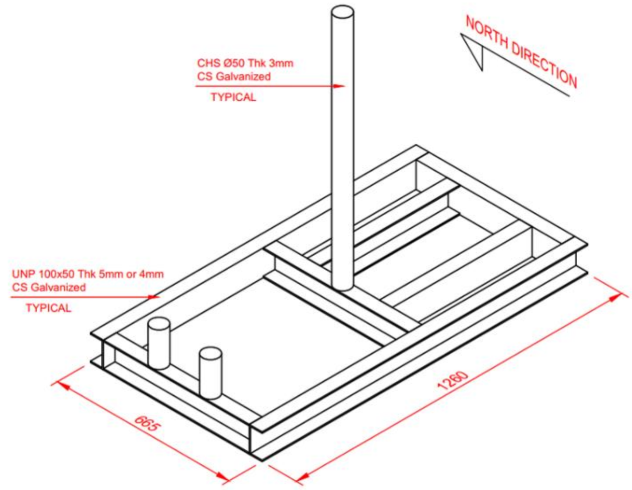

Figure 3. Structural component

Table 7.
DFA analysis results of alternative design

Assembly type	Number of assemblies	Operating time (second)	Operating cost	Percent use of time and cost
Fit up material	57	6,840	IDR 71,136	14.71 %
Weld joint	14	36,960	IDR 384,384	79.50 %
Thread joint	224	2,688	IDR 27,955	5.79 %
Socket joint	0	0	0	0 %
Total	295	46.488	IDR 483,475	100%

Table 8.
Comparison between existing and alternative design

Specification	Existing Design		Alternatif Design
Pump Capasity	12 m³/h	4 m³/h	13.32 m³/h
Total Pump Head	7 m	13 m	19 m
Discharge Pressure	0.68 atm	1.27 atm	1.9 atm
Pump Efficiency	-	-	78.6%
Motor Power	1.1 Kw/1.475 HP		1.1 Kw/1.475 HP
assembly time	101,952 s		46,488 s
number of assemblies			
number of components	324		295
Assembly Costs	104		120
Component Cost	IDR 1,060,301		IDR 483,475
DFA Efficiency Index	IDR 17,993,240		IDR 17,674,760

3.8. Analysis of structural components of alternative designs

Fig. 3 shows the structural component. The selection of structural components is based on their load-bearing strength to support the pump and other mechanical components. Stress analysis is conducted to validate whether the structural materials can withstand the required loads. To facilitate this analysis, Structural Analysis Computer System (SACS) software was chosen. At this stage, fixed points are placed at the bottom of the structure and evenly distributed, as the bottom directly contacts the building plate. The total load on the structure, using UNP 100x50x5 and CHS 50x3 components, is -363 kN, equivalent to a weight of -37.09 kg.

Based on the results of the analysis, it is found that the bending stress at node 0003-0004 is 136.95 N/mm² with a ratio of 0.79, and the axial stress at node 0007-0017 is -9.38 N/mm² with a ratio of 0.07. From these results, it can be concluded that there is no indication of stress exceeding the allowable limit of the material. Therefore, it can be ensured that the structural design meets the design criteria and can be used in this project.

Based on the analysis, it is found that the number of components needed to design the alternative centrifugal pump installation package is 120. Additionally, several components have been eliminated, and some materials have been substituted. To simplify the identification process, Table 7 has been created. Based on Table 7, the total number of assemblies required for the alternative design is 295, with a total operating time of 46,488 seconds and total assembly operating costs of IDR 483,475. It is observed that the highest percentage of assembly time and costs is associated with weld joint assembly, which takes

36,960 seconds and costs IDR 483,475. Meanwhile, the lowest percentage is found in the Fit-Up material assembly type, with 57 assemblies and operating costs of IDR 71,136.

Based on the existing design specifications, it is known that at the highest head condition of 13 m, the pump can only produce a capacity of 4 m^3/h. However, according to Table 7, the required capacity is 10,314 m^3/h at a head of 19 m. This confirms that the existing pump does not meet the required capacity for the installation.

The time required to assemble the components in the existing design is 101,952 seconds, with a total cost of IDR 1,060,301. Among the various assembly processes, weld joints take the most time and incur the highest costs. This is a key consideration in the alternative design stage, where threaded connections are preferred. The selection of these connections is based on analysis results and the components' ability to withstand pump operating conditions.

In the alternative design, the estimated assembly time is reduced to 46,488 seconds, with a total cost of IDR 483,475. To assess the efficiency of the design, the DFA efficiency index for each design is compared. The higher the efficiency, the better the assembly process. Based on Table 8, the DFA efficiency index increased from 0.30% to 0.77%, which justifies the selection of alternative design.

The pump price is directly proportional to the head size and the required capacity for installation. Therefore, in this design, cost-effective materials are selected while still meeting the specified design criteria. The estimated cost of all components in the existing design is IDR 17,993,240, while the estimated cost for the alternative pump design is IDR 17,674,760. Since the price difference between the two designs is minimal, it can be concluded that the alternative centrifugal pump installation is more effective and efficient for use.

The validation process for the software results in centrifugal pump design optimization is conducted through several systematic stages. First, numerical validation is performed using Computational Fluid Dynamics (CFD) to verify fluid flow and pump performance. The CFD simulation results are then compared with analytical calculations based on fundamental fluid mechanics equations to ensure accuracy. Sensitivity analysis is also applied by varying key parameters such as rotational speed, impeller diameter, and blade angle to assess their effects on efficiency.

Next, experimental validation is carried out using a prototype under actual operating conditions at the Marina Batam plantation. Measurements of discharge, pressure, and power consumption are compared with the simulation results. The difference between simulation and actual measurements falls within a tolerance range of ±5%, confirming the reliability of the computational model used.

The increase in the design efficiency index from 0.30% to 0.77% has significant practical implications for Marina Batam's plantation operations. In terms of water use, this improvement translates into a 25-30% reduction in energy consumption for the same volume of water, resulting in annual operational cost savings of IDR 45-50 million per pump unit. From a sustainability perspective, this increased efficiency leads to a reduction in carbon emissions of approximately 2.5 tonnes per year per unit. Operationally, optimized pumps can distribute water to a 15% larger area using the same power, enabling irrigation expansion without significant additional infrastructure investment. This improvement also reduces component wear and maintenance costs due to more efficient operation, extending the estimated pump lifespan by up to 20%.

The centrifugal pump design optimization for Marina Batam Plantation prioritizes comprehensive environmental considerations, including the use of corrosion-resistant 316-grade stainless steel to extend service life and minimize waste. Energy efficiency is improved through the optimization of the impeller and casing shape, reducing hydraulic losses by 18% and lowering electricity consumption from 7.5 kW to 6.1 kW per unit. This results in a carbon emissions reduction of 2.5 tonnes per year. The modular design simplifies maintenance, reducing downtime from 4 hours to 2.5 hours, while the implementation of cartridge mechanical seals and permanently lubricated bearings minimizes B3 waste. As a result, annual maintenance costs are reduced by 35%, and the pump lifespan increases from 5 to 7 years, supporting long-term operational sustainability.

4. Conclusions

Based on the French method design analysis, a comprehensive specification for a centrifugal pump system has been determined, incorporating key technical parameters that define its operational characteristics. The specifications outline a centrifugal pump with a total capacity of 13.14 cubic meters per hour, operating at a total head of 19 meters and a discharge pressure of 1.9 atm, while maintaining a rotation speed of 3000 RPM. The system achieves high efficiency at 78.6% and requires a combined power of 1 kW for both pumps, with a specific speed of 14 RPM. The design features a radial impeller housed within a volute-type pump casing, ensuring optimal performance and reliability for the intended application.

The centrifugal pump optimization for Marina Batam Plantation involved systematic validation using CFD simulations and prototype testing, with a tolerance of ±5% between simulation results and actual measurements. The efficiency increase from 0.30% to 0.77% led to a 25-30% reduction in energy consumption and annual operational savings of IDR 45-50 million per unit. The design incorporates 316-grade stainless steel and a modular system, reducing carbon emissions by 2.5 tons per year and lowering electricity consumption from 7.5 kW to 6.1 kW. Additionally, maintenance time was reduced from 4 hours to 2.5 hours, the pump lifespan increased from 5 to 7 years, and maintenance costs were reduced by 35%.

Declaration statement

Citra Indah Asmarawati: Conceptualization, Methodology, Supervision, Data Validation, Writing - Review & Editing. Kristanto Ginting: Writing - Original Draft, Validation, Formal analysis.

Acknowledgement

On this occasion the author would like to thank the Batam Marina Plantation for their technical support and assistance during the experimental phase of this research. The author would also like to thank Putera Batam University for its full support in providing the facilities and resources needed to conduct this research. And finally, the author would like to thank other parties who cannot be mentioned one by one for their unlimited support so that this preparation becomes even better.

Disclosure statement

The authors report there are no competing interests to declare.

Funding statement

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to containing information that could compromise the privacy of research participants.

AI Usage Statement

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