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Design of a Hydraulic System for a Glycerin Waste Mixer Machine Using Finite Element Method

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Abstract

This study presents the design of a hydraulic-based glycerin waste mixer machine, intended for use in the cement industry as a sustainable alternative to coal. Glycerin waste, a byproduct of biodiesel production, has a calorific value of 25,175.98 kJ/kg, making it a viable substitute fuel. However, its high viscosity and tendency to solidify at low temperatures pose significant challenges for processing. This research addresses these challenges by designing a hydraulic mixer with structural strength verified through Finite Element Method (FEM) analysis. The design follows the Ulrich & Eppinger product design approach, including concept development, technical specifications, and hydraulic system planning. Using Autodesk Fusion 360, the machine's frame, made of ASTM A36 steel, withstood loads with a maximum stress of 87.5 MPa and a safety factor of 2.83, ensuring its structural integrity. The hydraulic system, employing a double-acting cylinder operating at 10 bar, requires a motor power of 4.09 kW and achieves a fluid flow rate of 235.5 L/min. Cost analysis revealed a 30.44% reduction in manufacturing costs compared to similar commercial machines, totaling IDR 16.7 million. These findings demonstrate the efficiency, safety, and economic viability of the mixer, offering a promising solution for glycerin waste utilization in the cement industry.

Keywords: Glycerin Waste, Hydraulic System, FEM, Mixer Machine, Cost Efficiency

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1. Introduction

Industrial cement production is heavily reliant on fossil fuels, particularly coal, which contributes to high operational costs and substantial carbon dioxide (CO_2)

emissions [1]. These emissions have become a significant environmental concern, prompting industries to seek more sustainable alternatives to reduce both operational costs and the environmental impact of cement production. One promising alternative fuel is glycerin waste, a byproduct of the biodiesel production process, which has a calorific value of approximately 25,175.98 kJ/kg [2]. This energy content makes glycerin waste a viable candidate to partially replace coal in cement kilns, reducing dependency on fossil fuels and contributing to sustainable energy practices in the industry.

However, the utilization of glycerin waste presents several challenges due to its unique physical properties. Glycerin is highly viscous, tends to solidify at low temperatures, and is hygroscopic, which makes it difficult to handle [3]. These properties can lead to sedimentation, clogging of pipes, and operational instability during long-term storage, necessitating a continuous stirring system to maintain its homogeneity and prevent solidification. Traditional mechanical agitators, while commonly used in industrial mixing, are suboptimal for handling high-viscosity fluids like glycerin waste [4]. These systems require significant space and incur high operational and maintenance costs, which limit their applicability in certain industrial environments.

In contrast, hydraulic systems offer several advantages for mixing high-viscosity fluids. Hydraulic systems afford precise motion control and adjustable torque that suit high-viscosity fluids (e.g., glycerin waste). Hydraulic actuators have been applied to move and position mixing elements for viscous paints, demonstrating controllable vertical travel and operator handling benefits for dense materials [5]. Studies show that kinematic viscosity of fluids directly raises flow resistance and increases energy and torque demand, underscoring the need for proper hydraulic sizing and control to handle thick fluids efficiently [6]. Inline hydraulic mixing provides compact and space-efficient installations with smooth, tunable mixing. Jet-type hydraulic mixers have been demonstrated as compact inline devices with controllable performance for liquid mixing and extraction, offering an alternative to bulky mechanical agitators [7]. Moreover, effective mixing of high-viscosity fluids in small footprints has been illustrated through the optimization of hydrodynamics in compact passive/microstructured mixers [8]. These systems are widely used in industries where high torque and force control are essential, such as in waste management and fluid handling systems [9]. Hydraulic systems also provide a higher degree of safety, as they are less prone to mechanical failure due to their fewer moving parts compared to traditional mechanical systems [4].

From a structural design perspective, ensuring that the mixer frame can withstand the operational loads from the hydraulic cylinder, agitator, and fluid pressure is critical. The Finite Element Method (FEM) is an ideal tool for evaluating the structural integrity of the machine frame, ensuring that it has adequate strength, stiffness, and safety margins to withstand these loads without failure [10]. FEM analysis has been successfully used in similar studies to optimize the design of machinery in waste handling and material processing, where the strength of structural components is critical to ensure operational safety and longevity [11].

This study aims to address these challenges by designing a hydraulic-based glycerin waste mixer for use in the cement industry. The design follows the Ulrich and Eppinger product design approach, which incorporates concept development, technical specification definition, hydraulic system planning, and FEM-based structural analysis to ensure the machine's reliability. The unique contribution of this research lies in providing a hydraulic solution to handle glycerin waste efficiently while addressing the structural and operational challenges. The study also explores the potential for cost reduction, demonstrating that the proposed design is 30.44% more economical compared to existing commercial machines. Ultimately, this design offers a more sustainable and cost-effective solution for utilizing glycerin waste as an alternative fuel in cement production.

2. Methods

This study employs an engineering product design approach, utilizing Ulrich and Eppinger's method [12] along with structural analysis using the Finite Element Method (FEM), to ensure the strength and reliability of the mechanical and hydraulic systems of the glycerin waste mixer machine. The research is a numerical experiment and design engineering study, with the main stages including.

2.1 Observation and Problem Identification

In the production area of a cement plant using glycerin waste as a supplementary fuel, it was observed that the viscous glycerin often solidifies and clogs the lines, indicating a need for a stirring system to keep it in a liquid state. Primary data were obtained through direct observation and consultation with field operators, while secondary data were collected from supporting literature and journals [2], [3].

2.2 Design Stages Using Ulrich's Method

The use of Ulrich & Eppinger's product design approach is particularly suitable for this study due to its comprehensive and systematic structure, which allows for the integration of user requirements, technical specifications, and performance analysis within a single design cycle. This methodology was chosen over others for its well-established capability to guide the development of complex engineering designs, such as the hydraulic system for the glycerin waste mixer machine. The approach ensures that all relevant factors, including the properties of glycerin waste and the specific needs of the cement industry, are addressed in the design process. The first step involves identifying customer requirements and product functions, which are based on the challenging properties of glycerin—its viscosity, tendency to solidify, and its role as an alternative fuel in cement production. Following this, technical specifications such as tank volume, agitator rotational speed, torque, and hydraulic system capacity are defined to ensure the system's operational effectiveness. Multiple design concepts are then developed, exploring various transmission systems (e.g., belt, gearbox, or hydraulic) as well as different configurations for the tank and machine frame. These concepts are evaluated using an evaluation matrix, considering criteria such as manufacturing feasibility, operational efficiency, and ease of maintenance [13]. Finally, the best design concept is selected and developed further through 3D modeling using Autodesk Fusion 360 software. This iterative approach not only optimizes the design but also ensures that the final system is both technically sound and aligned with the objectives of enhancing glycerin waste processing in the cement industry.

2.3 Hydraulic System Design

The hydraulic system designed for the glycerin waste mixer utilizes a double-acting hydraulic cylinder, which operates at a maximum working pressure of 10 bar. The system’s pressure, essential for determining the necessary force to drive the mixer mechanism, is calculated using the basic formula for pressure:

$$\mathrm{P} = \frac{F}{A} \tag{1}$$

Where P is the pressure (in N/m²), F is the required thrust force (in Newtons), and A is the piston's cross-sectional area (in square meters) [14]. The force exerted by the hydraulic cylinder is essential for the efficient operation of the mixer, ensuring that it can handle the viscosity and density of glycerin waste.

The fluid flow rate, which is critical for controlling the speed and efficiency of the mixing process, is calculated by multiplying the cylinder’s movement velocity by the piston's cross-sectional area. This relationship is expressed in the following formula:

$$\mathrm{Q} = v\ x\ A \tag{2}$$

Where Q is the flow rate (in liters per minute), v is the velocity of the piston (in meters per second), and A is the cross-sectional area of the piston (in square meters). The fluid flow rate directly influences the mixing speed, which is crucial when dealing with high-viscosity fluids like glycerine [14].

To determine the required pump power for the hydraulic system, the following equation is used:

$$\frac{\rho\ x\ g\ x\ H\ x\ Q}{\eta\ x\ 1000} \tag{3}$$

Where ρ is the fluid density (in kg/m³), ggg is the acceleration due to gravity (9.81 m/s²), H is the total head (in meters), Q is the flow rate (in liters per minute), and η is the efficiency of the system (assumed to be between 85% and 90%) [15]. This formula allows for the calculation of the motor power necessary to maintain the desired flow rate, considering the energy losses within the system.

The working fluid selection is an important consideration in the hydraulic system's design. Given glycerin's chemical properties, glycerin-based fluids are appropriate for use in the hydraulic system, as they can effectively lubricate the system's components while maintaining compatibility with the waste material being processed.

2.4 Structural Strength Analysis Using Finite Element Method (FEM)

The 3D model of the machine frame and hydraulic system was imported into the Static Structural module of Autodesk Fusion 360 for structural analysis. In the simulation, the boundary conditions were set with fixed supports at the four corners (legs) of the frame to replicate the machine's operational setup. External loads of 500 N were applied at the hydraulic cylinder connection point, and an additional 200 N was applied on the surface of the tank. The frame material used was ASTM A36 steel, which has a yield strength (σy) of 250 MPa. The simulation calculated the maximum stress (von Mises stress) and total deformation under these applied loads, providing a comprehensive assessment of the frame's structural performance.

To evaluate the frame's safety under operational conditions, the Safety Factor (SF) was calculated using the following formula:

$$\mathrm{SF} = \frac{\sigma_y}{\sigma_{max}} \quad (4)$$

Where σy is the yield strength of the material (250 MPa), and σmax is the maximum stress experienced by the frame during the simulation [10]. This calculation ensures that the frame can withstand the applied loads without failing. A mesh convergence analysis was performed to ensure the accuracy and stability of the results, with an element size of 8 mm. The analysis showed a stress deviation of less than 5%, indicating that the simulation results were reliable.

The simulation results were compared with similar FEM studies in the literature, which reported safety factors in the range of 2 to 3 for similar structural designs. This comparison confirmed that the frame design meets the standard design requirements, with a safety factor of 2.83, which is within the acceptable range for industrial applications [16].

2.5 Design Simulation and Validation

The validation of the FEM simulation results was performed through manual calculations based on material strength theory, specifically focusing on the yield stress and deformation characteristics of the frame material [17]. To ensure the accuracy of the simulation, a detailed comparison was made between the FEM results and the theoretical calculations. This comparison revealed a deviation of 12.5% between the two, which is considered acceptable within industrial design tolerances. In typical engineering practice, deviations of less than 15% are acceptable, as they account for the inherent simplifications and approximations made in numerical modelling [16]. The acceptance criterion for the comparison was set based on industry standards, which allows for such deviations due to factors such as material heterogeneity and the complexity of the actual loading conditions, which may not be fully captured in the FEM model. Additionally, assumptions such as ideal boundary conditions, homogeneous material properties, and uniform load distribution were made during the validation process. These assumptions are common in initial design stages to simplify the analysis while still ensuring that the results are robust and reliable.

Furthermore, the hydraulic system was validated by calculating the total head loss in both the suction and discharge pipes using the Darcy–Weisbach equation, which is a standard method for determining fluid flow resistance in pipelines. The friction factor used for these calculations was assumed to be $f=0.02$, based on typical values for the chosen pipe material and flow conditions. This validation ensures that the hydraulic system's flow parameters, including pressure and flow rates, are consistent with real-world operating conditions.

2.6 Cost Budget Plan

A comprehensive cost estimate for the glycerin-waste mixer enumerated major assemblies—machine frame, hydraulic components (pumps, cylinders, valves), electric motor, gearbox/impeller drive, pulleys, and accessory fittings—and used supplier/unit-production pricing adjusted for material, labor, and fabrication to derive capital cost lines [5]. Viscosity-driven increases in torque and energy demand were included because kinematic viscosity raises pump and drive power needs, impacting both capital (larger pumps/gearbox) and operating costs [18]. Trade-offs between compact hydraulic/inline solutions (reducing footprint and some structural cost) and more complex/high-capital designs were assessed, incorporating inline/jet mixer options and previous findings on capital complexity for chaotic mixers [19]. CFD-led design iteration and mixer-geometry optimization were employed to trim manufacturing and commissioning contingencies in the estimate [20], [21].

The total manufacturing cost was then calculated by summing the individual costs of all components, along with any additional overhead expenses related to assembly, quality control, and testing. This approach ensures that all direct and indirect costs associated with the production of the machine are accounted for. Furthermore, the cost estimate was compared to that of similar commercial machines available in the market to evaluate potential cost savings. The comparison highlighted a 30.44% reduction in manufacturing costs, making the proposed design not only economically viable but also more competitive in the industry.

3.Results and Discussion

3.1 Frame Strength Analysis (FEM)

The machine frame was designed using hollow steel profiles (80 × 40 × 2 mm) made of ASTM A36 steel to support the loads from the agitator, hydraulic cylinder, and operational forces. ASTM A36 steel has a yield stress (σ_y) of approximately 250 MPa. **Figure 1** shows the frame model, which was subjected to reaction forces and an agitator load (nominal) of 500 N, with fixed supports at its four feet.

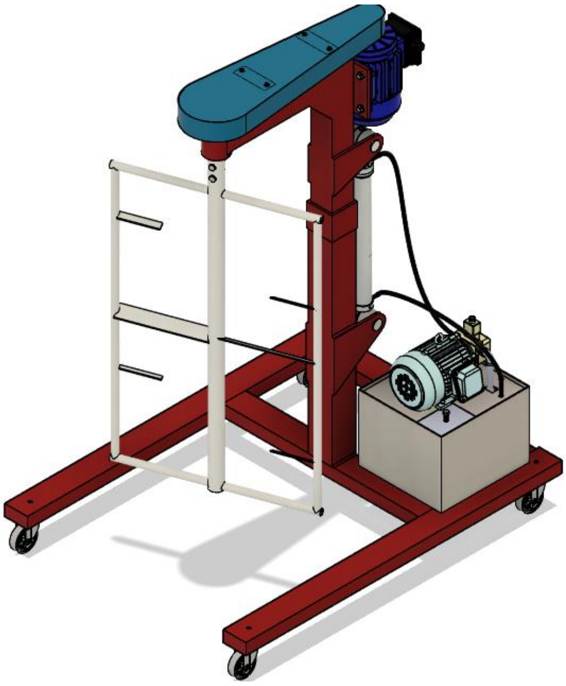

Figure 1. Design of the Glycerin Waste Mixer Machine

Figure 2. shows the simulation results of the Von Mises stress distribution in the frame, which were obtained using Autodesk Fusion 360. The simulation was carried out by applying a load of 500 N, representing the pushing force from the hydraulic cylinder at the cylinder mount, under fixed supports at the four feet of the frame. The frame material was ASTM A36 steel (yield stress $\sigma_y = 250$ MPa). The stress distribution indicates that the maximum stress (σ_{max}) of 87.52 MPa occurred at the joint between the cylinder mount and the main frame, while the minimum stress of 1.29×10^{-9} MPa occurred at the base of the support leg, which did not carry a direct load. The red region in the simulation results corresponds to the areas of highest stress, whereas the blue region corresponds to areas with very low stress. The maximum stress value is well below the yield stress of the material, indicating a safe design under the applied load.

The safety factor (SF) is conventionally computed as the material yield strength divided by the maximum von Mises stress obtained from a finite element method (FEM) analysis [22], [23]. Therefore, an SF of 2.83 mathematically implies the FEM-predicted peak stress is substantially below the material yield, meaning the structure can sustain approximately 2.83 times the applied load level before yielding [22]. An SF greater than unity is commonly interpreted as "safe," with values around or above 2 often adopted to provide a margin against uncertainties and variable loading; examples in engineering practice report safe and useful SFs of approximately 2.1 and higher where required [24], [25]. The use of ANSYS/FEM and von Mises criteria to derive these conclusions is standard practice for static strength assessment of frames and test stands [23]. These results align with those reported by individuals who noted a safety factor of approximately 3 for loads up to 20.000 N [26]. Furthermore, frame optimization using FEM can reduce weight by approximately 12% without compromising strength, as demonstrated in a study on an electric bus frame [27].

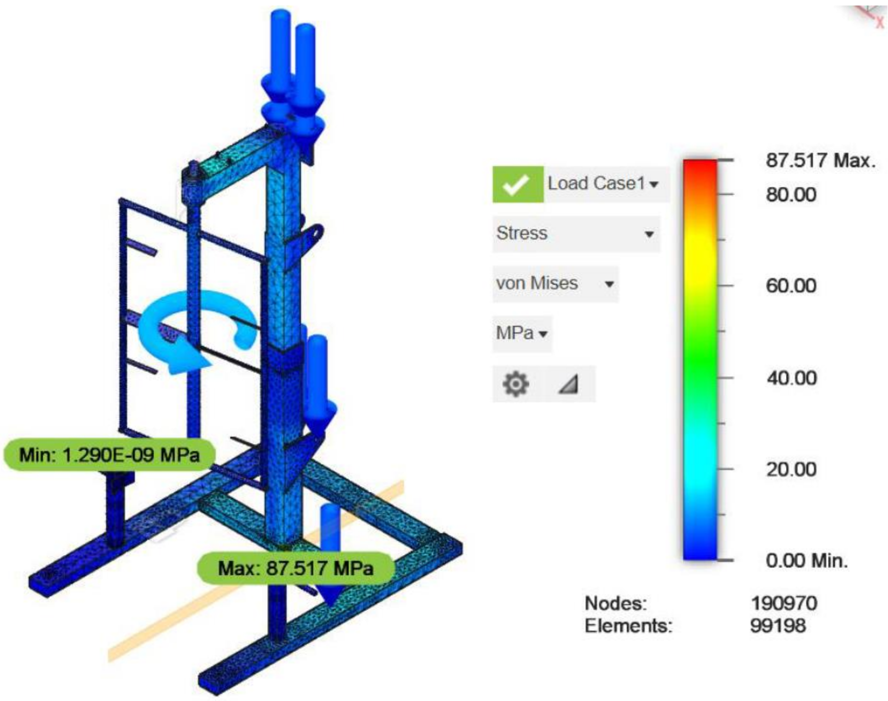

Figure 2. Von Mises Stress Distribution from FEM Simulation on the Frame of the Glycerin Waste Mixer Machine

In order to validate the model, theoretical calculations based on material strength theory were compared with the FEM results [17]. **Tabel 1**. presents the comparison between the theoretical calculations and the FEM simulation results:

The maximum deformation from the simulation was 1.52 mm, which is below the allowable deformation limit for the structure. This deformation occurred at the top of the hydraulic cylinder mount, but did not significantly affect the overall stability of the structure. The frame's good stiffness supports stable operation of the agitator when working with high-viscosity fluids. The comparison between theoretical and simulation results in **Tabel 1**. shows deviations of less than 15%, indicating that the numerical model is accurate and valid. This finding is consistent who suggest that deviations below 15% are acceptable for FEM simulations of lightweight steel structures [16].

Tabel 1. Theoretical calculations and the FEM simulation results

Parameter	Theoretical	FEM Simulation	Difference (%)
Maximum Stress	100 MPa	87.5 MPa	12.5
Maximum Deformation	1.68 mm	1.52 mm	9.5
Safety Factor	2.50	2.83	13.2

The frame design meets the mechanical safety criteria and can reliably handle the anticipated operational loads. The use of hollow profiles minimizes weight and material cost while maintaining stiffness and strength, consistent with the principles of efficient design [15].

3.2 Hydraulic System Planning

The hydraulic system is designed to drive a cylinder with a 50 mm bore diameter and a 1200 mm stroke, which will raise and lower the glycerin waste mixer. **Tabel 2**. shows the calculation results for the hydraulic system parameters.

Tabel 2. Hydraulic System Calculation Results

Parameter	Result	Description
Working Pressure	10 bar	Operational working pressure
Cylinder Thrust Force	1.960 N	Thrust to lift the agitator shaft
Fluid Flow Rate	235.5 L/min	At a cylinder speed of 0.02 m/s
Pump Power	3.54 kW	Pump efficiency assumed at 86.6%
Hydraulic Motor Power	4.09 kW	3-phase electric motor

Hydraulic system calculations in **Tabel 2**. indicate that a motor power of 4.09 kW is sufficient to achieve a working pressure of 10 bar and generate a thrust of approximately 1,960 N (about 200 kgf). The pump, assumed to have an efficiency of 86.6%, delivers the necessary power to drive the hydraulic system. Additionally, the system is equipped with a 12-bar relief valve for safety to prevent over-pressurization during operation [9]. The fluid flow rate of 235.5 L/min corresponds to a cylinder extension/retraction speed of 0.02 m/s under the specified conditions.

Viscosity-driven efficiency loss in centrifugal pumps is well established: as fluid viscosity rises, internal friction and flow resistance increase, lowering volumetric efficiency and requiring higher input power to maintain flow rates [28]. Empirical analyses indicate that optimal impeller geometry (blade count and shape) shifts with viscosity; for high-viscosity fluids, fewer blades or tailored profiles can reduce energy losses and improve operational performance [9]. Pump performance also depends on the operating point, and can suffer from issues such as cavitation or degraded efficiency across varying flow rates, making experimental characterization across expected viscosities and temperatures necessary [30]. A comprehensive study for glycerin-type wastes should combine controlled bench testing (flow, head, power vs. viscosity), impeller-geometry optimization, and numerical analyses to quantify efficiency curves, motor sizing margins, and derating strategies for varying glycerin mixtures and temperatures [29], [30].

Relevant literature suggests that a well-designed mixer and agitator should consider fluid circulation, impeller geometry, and optimal energy efficiency [4]. Hydraulic systems offer advantages in providing more flexible thrust control compared to mechanical agitators or direct pumping systems [9]. The hydraulic control system is designed with a flow control valve and a pressure relief valve set at 12 bar for safety. Technical evaluation shows that this hydraulic system enables precise movement, from low to high speeds (a 1200 mm stroke in 60 seconds → v = 0.02 m/s), and delivers sufficient torque to handle the high viscosity of glycerin waste. This aligns with the principles of mixing equipment design, which consider both mechanical and process aspects [31].

3.3 Manufacturing Cost and Design Efficiency

The manufacturing cost of the glycerin waste mixer machine was calculated using standard unit production prices (HSPP) for all major components, including the frame material, hydraulic system components, electric motor, gearbox, pulleys, and the associated manufacturing processes. The total manufacturing cost was estimated at IDR 16,695,500, which represents a significant cost saving of 30.44% compared to a comparable commercial machine. This cost reduction is attributed to several key factors.

Firstly, the selection of ASTM A36 steel as the frame material is supported by its demonstrated balance of strength, stiffness, and cost, as noted in literature examining comparable chassis and frame studies [32], [33]. Finite Element Analysis (FEA) validated the structural capacity using the von Mises/yield-strength safety-factor definition, supporting a safety factor (SF) of approximately 2.05, as reported in recent literature [33]. Optimization approaches, similar to those reported in structural engineering studies, could potentially yield mass reductions while maintaining structural integrity; these methods suggest a feasible reduction in weight and material costs, as well as decreases in waste and fabrication time [34]. This aligns with findings that support weight reduction strategies through advanced design methods that streamline geometry and reduce raw-material usage.

Secondly, the hydraulic system was cost-optimized by selecting components and tuning hydraulic parameters to the glycerin-waste duty, leveraging energy-saving architectures, such as variable-displacement pumps and speed-controlled drives, to match power to demand and avoid costly oversizing [35]. System losses occur across pumps, valves, hoses, and actuators; therefore, targeting these elements through optimal pump type, control strategy, and piping reduces both capital and operating costs [36]. Additionally, designing for minimal pressure loss and incorporating built-in safety mechanisms and redundancy further improve life-cycle cost and reliability [37]. Practical tailoring of the system is facilitated by axial-piston and swash-plate technologies that permit precise pump power matching to the varying viscosity and flow requirements of glycerin mixtures, thereby limiting unnecessary motor sizing and energy consumption [38], [39].

Lastly, Simplifying the machine design—standardized parts, DFMA-aligned assemblies, and a modular hydraulic package—reduces assembly labor and shop time and speeds field integration/testing by enabling off the shelf procurement, parallel subassembly work, and plug in verification of hydraulic modules [35], [40]. Standard hydraulic units (e.g., axial piston/swash plate modules) and common fasteners shorten fabrication and commissioning while preserving controllability and safety, lowering both labor hours and lifetime maintenance effort [37], [38], [39]. Targeting system losses and selecting matched pump/motor families permit right sizing without bespoke manufacture, further cutting component lead time and assembly complexity [35], [36]. The combined approach—material standardization, DFMA, modular hydraulics, and component matching—therefore provides demonstrable reductions in labor, assembly time, and integration cost while retaining performance and serviceability [33], [36], [40].

The combination of these factors—optimized material selection, reduced weight, careful hydraulic system design, and simplified assembly—contributed to the 30.44% reduction in manufacturing costs compared to similar commercial machines. The use of FEM for frame optimization not only improved the machine's structural performance but also allowed for material savings, which directly influenced the cost efficiency of the manufacturing process.

4. Conclusion

The results of this study indicate that the frame of the glycerin waste mixer machine, constructed from ASTM A36 steel, possesses adequate strength and stiffness, with a maximum stress of 87.5 MPa and a safety factor of 2.83, ensuring it is safe under operational loads. The hydraulic system, operating at a working pressure of 10 bar, can generate a thrust of 1,960 N, a fluid flow rate of 235.5 L/min, and requires a motor power of 4.09 kW, meeting the stirring process requirements.

The 12.5% deviation between the simulation and theoretical results confirms the model's validity. Economically, the total manufacturing cost of IDR 16,695,500 is 30.44% lower than that of a comparable commercial machine, demonstrating the design's cost-effectiveness. Based on these findings, the design of the glycerin waste mixer is deemed feasible, efficient, and suitable for implementation in the cement industry as a sustainable alternative fuel. However, there are areas where further research could enhance the system's performance and applicability. Future studies could test the system under varying environmental conditions, such as temperature fluctuations that may affect the viscosity of glycerin waste, to ensure consistent operation across different climates. Additionally, exploring automation options for the mixer, including integrating sensors and control systems for real-time monitoring and adaptive operation, could further improve efficiency and reduce operational costs. These improvements would not only optimize the system's performance but also contribute to advancing the use of glycerin waste in industrial applications.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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References

[1] A. M. Ilham, Z. Helwani, and W. Fatra, "Densifikasi Produk Karbonisasi Pelepah Sawit Menjadi Briket Menggunakan Crude Gliserol Produk Samping Biodiesel Sebagai Filler," JOMFTEKNIK, vol. 3, no. 2, pp. 2–5, 2016.

[2] Suhartanta and Z. Arifin, "Pemanfaatan Minyak Jarak Pagar Sebagai Bahan Bakar Alternatif Mesin Diesel," J. Penelit. Saintek, pp. 19–46, 2008.

[3] P. J. Rowe, Raymond C. Sheskey, Handbook of Pharmaceutical Excipients, 6th ed. Pharmaceutical Press, 2009.

[4] T. Jirout and D. Jiroutova, "Application of Theoretical and Experimental Findings for Optimization of Mixing Processes and Equipment," 2020.

[5] O. I. Iyobosa, "Design and Construction of an Electrically Operated Paint Mixing Machine," J. Eng. Res. Reports, pp. 20–29, 2020, doi: 10.9734/jerr/2020/v14i317125.

[6] Ł. Warguła et al., "The Influence of Kinematic Viscosity of Oils on the Energy Consumption of a Gear Pump Used for Pumping Oil in Machines and Vehicles," PLoS One, vol. 20, no. 9, p. e0331371, 2025, doi: 10.1371/journal.pone.0331371.

[7] W. Piotrowski, R. Kubica, and M. Gądek, "Studies on a Novel Jet Mixer in the Extraction Process," Processes, vol. 11, no. 10, p. 2904, 2023, doi: 10.3390/pr11102904.

[8] D. Sun, W. Wang, Y. Ju, W. Song, Y. Li, and L. Li, "Shearing and Mixing Performance of Ultrahigh-Molecular-Weight Hydrolyzed Polyacrylamide (HPAM) Solution in a Helixes Static Mixer," Teh. Vjesn. - Tech. Gaz., vol. 28, no. 2, 2021, doi: 10.17559/tv-20190712015659.

[9] J. V Karaeva, G. R. Khalitova, D. A. Kovalev, and I. A. Trakhunova, "Study of the Process of Hydraulic Mixing in Anaerobic Digester of Biogas Plant" no. March, 2015, doi: 10.1515/cpe-2015-0008.

[10] A. B. Prasetiyo and K. A. Sekarjati, "Finite Element Simulation of Power Weeder Machine Frame," vol. 4, no. 2, 2022.

[11] A. Berardi et al., "FEA for Optimizing Design and Fabrication of Frame Structure of Elevating Work Platforms," pp. 1–15, 2025.

[12] K. T. Ulrich and S. D. Eppinger, Product Design and Development. McGraw-Hill/Irwin, 2012.

[13] I. M. L. Batan, Desain Produk, Pertama. Inti Karya Guna, 2012.

[14] Praw, A. Prasetyo, and Gunawan, Hidrolika dan Pneumatika, 1st ed. Jakarta: Erlangga, 2003.

[15] R. . Khurmi and J. . Gupta, Machine Design. Eurasia Publishing House, 2005.

[16] R. Pratama, R. Effendi, M. Qadri, and A. Y. Nasution, "Analysis of The Frame Design of Cracker Sheet Printing and Cutting Machine Using Finite Element Method Simulation," vol. 12, no. 1, pp. 7–13, 2024.

[17] R. L. Mott and J. A. Untener, Applied Strength of Materials, 7th ed. CRC Press, 2021.

[18] A. Rahimzadeh, F. Ein-Mozaffari, and A. Lohi, "New Insights Into the Gas Dispersion and Mass Transfer in Shear-Thinning Fluids Inside an Aerated Coaxial Mixer via Analysis of Flow Hydrodynamics and Shear Environment," Ind. Eng. Chem. Res., vol. 61, no. 10, pp. 3713–3728, 2022, doi: 10.1021/acs.iecr.1c04586.

[19] A. Costine, P. D. Fawell, A. Chryss, S. Dahl, and J. Bellwood, "Development of Test Procedures Based on Chaotic Advection for Assessing Polymer Performance in High-Solids Tailings Applications," Processes, vol. 8, no. 6, p. 731, 2020, doi: 10.3390/pr8060731.

[20] A. M. Díaz, I. Terrones-Fernandez, P. J. Gamez-Montero, and R. Castilla,

"Helical Static Mixer Simulations for Its Integration in the Pour Plate Method: Mixing Agar and a Nutrient Solution," Energies, vol. 16, no. 15, p. 5816, 2023, doi: 10.3390/en16155816.

[21] S. J. Tan, K. H. Yu, M. A. Ismail, C. F. Goh, and K. B. Lua, "Numerical Investigation of in-Line and Staggered Fins Arrangements on Liquid Mixer," J. Brazilian Soc. Mech. Sci. Eng., vol. 46, no. 3, 2024, doi: 10.1007/s40430-024-04733-0.

[22] L. A. N. Wibawa, "Static Stress Analysis and Fatigue Life Prediction of Rocket Motor Test Stand Using Numerical Simulation," R E M (Rekayasa Energi Manufaktur) J., vol. 6, no. 2, pp. 9–13, 2021, doi: 10.21070/r.e.m.v6i2.1533.

[23] D. H. Al-Janan et al., "Stress and Displacement Analysis of Powder Packaging Machine of Capacity 2,600 PCS/Hours," Iop Conf. Ser. Earth Environ. Sci., vol. 969, no. 1, p. 12018, 2022, doi: 10.1088/1755-1315/969/1/012018.

[24] F. Fernanda, Munirwansyah, and M. Sungkar, "Increase in Safety Factor Value in Existing Conditions and Reinforcement of Gabion Type Retaining Wall Pt. Medco E&P Malaka Block A," E3s Web Conf., vol. 476, p. 1014, 2024, doi: 10.1051/e3sconf/202447601014.

[25] F. A. N. biomej et al., "Torque Load Analysis on Rear Axle Shaft Material AISI 4340 Normalized," Biomed. Mech. Eng. J., vol. 2, no. 2, pp. 36–40, 2023, doi: 10.33005/biomej.v2i2.59.

[26] C. Tabayyun, "Analisis Frame Meja Dandori Menggunakan Metode Finite Element Analysis (FEA)," vol. 04, no. 02, pp. 77–87, 2025.

[27] Z. Yang, B. Deng, M. Deng, and G. Sun, "A Study on Finite Element Analysis of Electric Bus Frame for Lightweight Design," vol. 03049, pp. 1–4, 2018.

[28] N. H. K. Anuar, M. N. M. Razali, M. R. M. Yasin, M. A. Hadi, and A. N. A. Ghaffar, "Study on Custom Centrifugal Pump Performance in Supplying Food Based High Viscos Liquid," J. Mod. Manuf. Syst. Technol., vol. 5, no. 1, pp. 80–88, 2021, doi: 10.15282/jmmst.v5i1.6280.

[29] A. A. Mohammedali, A. A. M. Omara, I. R. Mohamed, H. Mohamed, and D. Mohamed, "Performance Assessment of a Centrifugal Pump With Varying Blade Counts and Fluid Viscosities Through Euler Head and Entropy Production Analysis," Eng. Reports, vol. 7, no. 4, 2025, doi: 10.1002/eng2.70105.

[30] İ. Sezer and Y. S. Şahin, "Experimental Investigation of Centrifugal Pump Characteristics," Int. J. Adv. Nat. Sci. Eng. Res., vol. 7, no. 4, pp. 408–414, 2023, doi: 10.59287/ijanser.755.

[31] D. S. Dickey and J. B. Fasano, "Mechanical Design of Mixing Equipment," in Handbook of Industrial Mixing: Science and Practice, John Willey & Sons, Inc, 2004.

[32] A. B. Seelam, A. K. A. Ahmed, and K. H. Sachidananda, "Buggy Role Cage – Analysis and Design," Int. J. Saf. Secur. Eng., vol. 10, no. 5, pp. 589–599, 2020, doi: 10.18280/ijsse.100502.

[33] M. H. Tullah et al., "Design and Evaluation of Hollow Frame Structures for the Development of Urban-Centric Two-Passenger Electric Vehicles," Eastern-European J. Enterp. Technol., vol. 5, no. 7 (125), pp. 80–86, 2023, doi: 10.15587/1729-4061.2023.289232.

[34] S. H. Asif, K. Hasan, and N. R. Dhar, "Topology Optimization and 3D Printing of a Unibody Quadcopter Airframe," Iop Conf. Ser. Mater. Sci. Eng., vol. 1305, no. 1, p. 12021, 2024, doi: 10.1088/1757-899x/1305/1/012021.

[35] A. C. Mahato and S. K. Ghoshal, "Energy-Saving Strategies on Power Hydraulic System: An Overview," Proc. Inst. Mech. Eng. Part I J. Syst. Control Eng., vol. 235, no. 2, pp. 147–169, 2020, doi: 10.1177/0959651820931627.

[36] K. Pate, J. R. Marschand, F. Breidi, T. Salem, and J. Lumkes, "Design and Sensitivity Analysis of Mechanically Actuated Digital Radial Piston Pumps," Processes, vol. 12, no. 3, p. 504, 2024, doi: 10.3390/pr12030504.

[37] R. Petrović, A. Banaszek, M. Andjelković, H. R. A. Qananah, and K. A. Alnagasa, "Experimental Tests of the Piston Axial Pump With Constant Pressure and Variable Flow," Designs, vol. 8, no. 1, p. 5, 2023, doi: 10.3390/designs8010005.

[38] N. Todić, S. Savić, D. Gordić, and R. Petrović, "Experimental Research of the Hydrodynamic Processes of an Axial Piston Water Hydraulic Pump," Machines, vol. 10, no. 9, p. 728, 2022, doi: 10.3390/machines10090728.

[39] G. Sun, K. Cui, M. Liu, J. Zhang, Y. Sun, and X. Yang, "Design and Analysis of the Integrated Linear Actuation Module of the Swash Plate for Piston Pump/Motor," J. Phys. Conf. Ser., vol. 3097, no. 1, p. 12014, 2025, doi: 10.1088/1742-6596/3097/1/012014.

[40] D. Dong, Y. Zou, H. Pan, G. Zhou, F. Yu, and Y. Tang, "DFMA-oriented Modular and Parametric Design and Secondary Splitting of Vertical PC Components," Sci. Rep., vol. 13, no. 1, 2023, doi: 10.1038/s41598-023-30192-z.