

Article

Design Optimization of Knock-Down Biomass Pyrolyzer for Small and Medium Enterprises Using Value Engineering and Fault Tree Analysis

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Abstract: Small and medium enterprises in rural Indonesia are central to local growth yet often lack efficient rice husk waste management, with open burning still prevalent. This study designs an accessible knock-down biomass pyrolyzer for rural and home-scale SMEs by integrating Value Engineering and Fault Tree Analysis. The method combines functional analysis, cost breakdown, targeted simulations, and risk mapping to prioritize high-leverage improvements. The selected design includes load-indicator washers, modular knock-down joints, high-efficiency insulation, and stiffer rings in the condenser. Results indicate a structural failure risk reduction of up to 30 percent, a thermal efficiency gain of 10 to 15 percent, and only a 5.5 percent increase in production cost. Fault Tree Analysis attributes 50 percent of failures to design, 33.3 percent to assembly, and 16.7 percent to materials, while simulations show markedly lower bulging deformation, enhancing operational reliability. The final configuration is robust, quick to assemble, and well suited to rural constraints, enabling safer and more productive valorization of rice husk. The integrated approach offers a practical pathway to strengthen SME competitiveness, improve equipment reliability, and advance circular economy practices in Indonesia.

Keywords: Fault Tree Analysis, Pyrolysis Reactor, Rice Husk Waste, Sustainable Design, Value Engineering

Citation: Rudiantama, M. R., Zakwan, M. A., Khair, F., Maksum, A. (2026). Design Optimization of Knock-Down Biomass Pyrolyzer for Small and Medium Enterprises Using Value Engineering and Fault Tree Analysis. *Recent in Engineering Science and Technology*, 4(02), 103–116. Retrieved from <https://www.mbi-journals.com/index.php/riestech/article/view/131>.

Academic Editor: Vika Rizkia

Received: 23 October 2025

Accepted: 17 January 2026

Published: 30 April 2026

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1. Introduction

Indonesia, as one of the largest rice producers in the world, generates more than 53 million tons of paddy annually, resulting in approximately 10.8 million tons of rice husk waste each year[1]. Although rice husk is rich in silica and possesses significant economic potential, its utilization remains far from optimal[2]; most of the waste is still openly burned, polluting the air and increasing carbon emissions[3], [4]. Pyrolysis technology has emerged as an efficient and sustainable thermal solution that thermochemically decomposes biomass at temperatures of 300–700°C in the absence of oxygen, converting rice husk into value-added products such as rice husk ash (RHA), bio-oil, and producer gas[5], [6].

At the small and medium industrial (SME) scale, the knock-down design has become the main choice due to its ease of assembly, mobility, and maintenance. [7]. However, field tests and simulations have revealed persistent mechanical failures in the condenser section, such as flange leakage, bulging, and joint instability, all of which directly affect operational reliability, safety, and equipment lifespan[8], [9].

The risk of mechanical failure in biomass pyrolyzer systems is often exacerbated by improper material selection, inadequate structural reinforcement, and inconsistent assembly quality[10]. Therefore, a data-driven reliability assessment is essential to systematically map failure pathways, prioritize the most critical risks, and design effective improvements. Fault Tree Analysis (FTA), as an internationally recognized failure

analysis technique (IEC 61025:2019), provides a structured top-down approach for identifying and mitigating risk in mechanical systems and has been shown to lower overall production costs by an average of 8–12%[11]. Building upon this, the present research explores the redesign of a biomass pyrolyzer by applying Value Engineering (VE) principles as the core methodology, with FTA supporting the identification and mitigation of key risk components. The novelty of this study lies in integrating detailed VE functional analysis with simulation-based validation, enabling proposed design alternatives to be evaluated both economically and thermally[12]. Ultimately, the aim is to improve cost efficiency, simplify fabrication, and enhance usability that employing a combination of cost optimization strategies and simulation-based validation resulted in a reduction of unscheduled downtime by 20% in industrial systems, thereby making biomass pyrolyzer technology more accessible to SMEs and better aligned with circular economy objectives[13], [14].

To better understand the sources of mechanical failure in knock-down biomass pyrolyzer systems, a process block diagram is presented in **Figure 1**. This diagram illustrates how poor material selection, insufficient structural reinforcement, and inconsistent assembly quality interact to create critical failure pathways, ultimately compromising system reliability and safety.

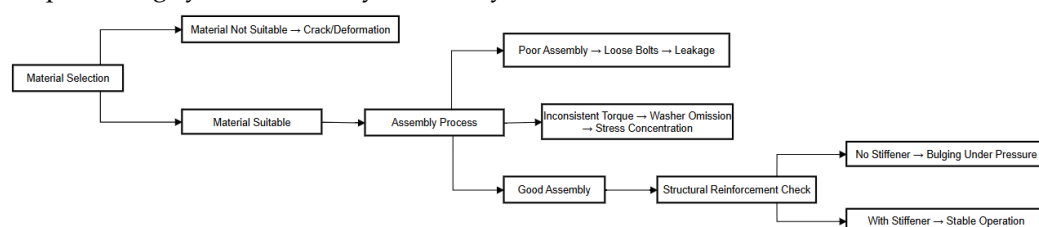


Figure 1. Block Diagram

Recent research on biomass pyrolysis systems for small and medium enterprises (SMEs) has highlighted recurring challenges in both mechanical reliability and operational efficiency. Babajo et al. (2021) developed and tested a co-pyrolysis system for liquid fuel production, emphasizing the importance of design robustness and performance optimization in small-scale applications[15]. However, their study did not systematically address risk prioritization or failure mitigation for long-term use.

In 2022, Mohamad Ramadani conducted an evaluation of the same knock-down pyrolysis tank design for use in community and small to medium-scale industries [9], [16]. However, the scope of his research was limited primarily to flow simulation analysis, without a comprehensive assessment of overall system feasibility or failure risks. In the same year, Faiz Irza performed a CFD-based study focusing on the condenser section of a rice husk pyrolysis system, also employing the knock-down design concept[17], [18]. Nevertheless, neither study addresses the broader issues of system reliability nor provides an integrated failure and feasibility analysis covering the complete pyrolyzer system. The present study builds upon these previous works by implementing a holistic approach that combines Value Engineering and Fault Tree Analysis, thus enabling a more robust evaluation of both functional value and mechanical reliability across all subsystems, as documented in this research.

Badida et al. (2019) demonstrated the effectiveness of fuzzy fault tree analysis in risk evaluation for process equipment, showing how a structured top-down failure mapping can guide more targeted improvements in reliability [12]. Similarly, Wu (2021) applied Fault Tree Analysis (FTA) for safety assessment in LNG plants, reinforcing FTA's suitability as a standard for mechanical risk mapping in complex thermal systems [10]. These works support the use of FTA as an analytical backbone for identifying and quantifying critical failure modes in pyrolyzer design.

On the economic and functional optimization side, Akerekan et al. (2024) and Prilutskaya et al. (2021) underscored the value of systematic Value Engineering (VE) in enhancing both sustainability and cost-effectiveness in manufacturing system redesigns [19], [20]. They show that the SAVE International job plan, combined with simulation validation, enables designers to balance functional performance and economic constraints in process equipment development. Nevertheless, most studies treat VE and FTA in isolation, and only a limited number apply them simultaneously within the context of SME-scale biomass pyrolyzer systems.

Based on this gap, the present research integrates VE and FTA into a single framework for redesigning a knock-down biomass pyrolyzer targeting SMEs, utilizing simulation and empirical risk mapping as validation tools. This integrated approach responds directly to the shortcomings in the literature by addressing both reliability and cost-effectiveness through a combined, quantitative method, as previously recommended by Badida et al. (2019) and Akerekan et al. (2024).

2. Materials and Experiment Methods

This study focuses on the condenser subsystem of a knock-down type biomass pyrolyzer, which is designed for small and medium enterprises (SMEs) to process rice husk into biochar, bio-oil, and producer gas. The condenser is a critical component, constructed as a cylindrical vessel with an approximate weight of 100 kg (diameter 544 mm, height 1000 mm), and is connected to the main reactor using flanged and bolted joints. Field prototypes operate at temperatures up to 400°C, exposing the condenser to significant thermal and mechanical loads.

2.1 Materials

The analysis in this study is based on multiple data sources that complement each other to ensure both technical validity and contextual relevance for the design of a knock-down biomass pyrolyzer. First, technical drawings and specifications from previous research, along with data from field-tested prototypes, serve as the primary references for assessing the performance and structural configuration of the initial design. Historical failure data collected during assembly and testing processes provide insights into real-world failure modes, such as deformation, leakage, and joint instability.

Additionally, material property data, specifically for ASTM A36 structural steel for base frame and leg support material and AISI 304 stainless steel, are utilized due to their known strength, thermal resistance, and corrosion resistance, especially for components in contact with pyrolysis outputs like bio-oil and syngas[20]. Mechanical simulations were conducted using Solidworks software to analyze critical aspects such as bulging deformation, von Mises stress distribution, and displacement, as well as to validate structural reliability under operational loads.

Furthermore, the analysis integrates information from the previous Bill of Materials (BOM), which is essential for conducting Value Engineering (VE). The analysis allows for evaluation of the cost-to-function ratio of each component, enabling redesign recommendations that are both risk-informed and cost-effective.

2.2 Methods

This study employs a dual-methodology approach, combining Fault Tree Analysis (FTA) for reliability risk assessment with Value Engineering (VE) for design optimization of the knock-down biomass pyrolyzer system. Both methods are applied systematically to ensure that the proposed design modifications address critical mechanical failures and deliver functional and economic value improvements. The integration of these methodologies enables a comprehensive evaluation that bridges the gap between technical reliability and cost-effective engineering solutions.

2.2.1 Fault Tree Analysis (FTA)

The analysis begins by defining the top event, namely, mechanical failure in the condenser that could potentially lead to operational shutdown or hazardous leakage. Subsequently, the failure structure is broken down into several main branches, namely failures due to design, materials, and assembly processes. The interrelationships among causal factors in each branch are mapped using AND/OR logic gates to represent cause interactions, such as bulging, which only occurs if the stiffener is insufficient and there is excess internal pressure[10]. All possible failure pathways are then analyzed for frequency and criticality to identify the most dominant minimal cut sets. Once the quantitative risk contribution of each branch is determined based on its frequency of occurrence in the minimal cut sets, all findings are validated by comparing them to field test results and static simulation data to ensure the accuracy and relevance of the FTA analysis performed.

2.2.2 Value Engineering (VE) Procedure

The research methodology is structured according to the standard job plan of SAVE International for Value Engineering, which comprises five main phases[23]. In the Information Phase, the functional decomposition of the pyrolyzer system was conducted, classifying functions into basic, secondary, and support categories[24]. Cost data were compiled from previous prototype bills of materials, supplier quotations, and fabrication records to establish a baseline for economic evaluation[20]. During the Creative Phase, design alternatives were generated through structured brainstorming, including options such as replacing welded joints with knock-down bolted assemblies, altering frame materials, and incorporating high-efficiency ceramic insulation[25], [26].

In the Evaluation Phase, each design alternative was assessed using a weighted scoring matrix based on four primary criteria: thermal efficiency, durability, manufacturability, and potential cost savings. The value index, the function-to-cost ratio, was calculated for each component to guide selection. Selected alternatives were further analyzed in the development phase, where three-dimensional models were created in Solidworks and subjected to thermal and structural simulations. These simulations included thermal gradient analysis, bulging simulations of the condenser, and an assessment of insulation performance.

Finally, in the Presentation Phase, the most viable redesigns were consolidated into an integrated final model. Risk analysis used Fault Tree Analysis (FTA) to systematically map and quantify potential failure modes, focusing on the condenser and joint assemblies. This integrated approach ensured that both functional and reliability improvements were supported by quantitative analysis and simulation-based validation.

2.2.3 Simulation and Risk Analysis

Simulation tools were employed to evaluate the thermal and mechanical performance of the redesigned components. Finite Element Analysis (FEA) was conducted on critical areas such as the condenser wall, where bulging deformation was previously observed[9,25]. Heat transfer analysis compared the performance of various insulation alternatives. Concurrently, Fault Tree Analysis (FTA) was used to define the top failure event and trace the contributing sub-events through logic gate modeling. The FTA structure included domains such as design flaws, material limitations, and assembly errors, enabling prioritization of mitigation strategies.

3. Results and Discussion

Before presenting the detailed findings, it is important to reiterate that this study aims to enhance the reliability, efficiency, and cost-effectiveness of the knock-down biomass pyrolyzer system, focusing on the condenser unit as a critical component. The results are systematically organized to comprehensively analyze mechanical failure pathways, design modifications, and the impact of Value Engineering (VE) interventions. By integrating Fault Tree Analysis (FTA) and VE methodologies, the research delivers a

holistic evaluation that identifies and quantifies failure modes and proposes practical, data-driven improvements directly relevant to small and medium-sized enterprises (SMEs). The following sections present the results of the FTA and VE analyses, highlight key mechanical risks and their mitigation strategies, and discuss the overall benefits of the proposed design enhancements in terms of performance, manufacturability, and compliance with international safety standards.

3.1. Mechanical Failure Pathways in the Condenser

Figure 2 shows the Fault Tree Analysis (FTA) diagram developed for the condenser subsystem of the knock-down pyrolyzer.

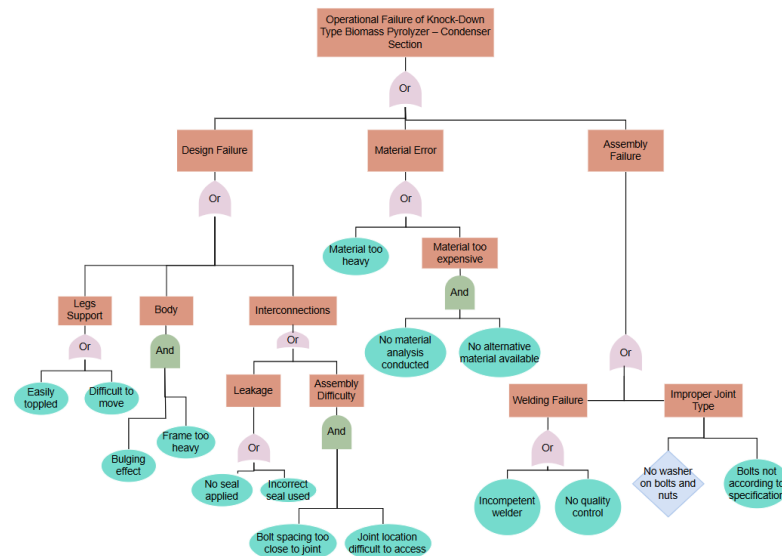


Figure 2. Structure of the FTA Tree

The diagram systematically maps the logical relationships among the main causes of mechanical failure, ranging from flange joint leakage and bulging deformation of the vessel wall to misaligned mechanical assembly. At the top level, the analyzed top event is a mechanical failure that leads to operational shutdown or the risk of hazardous leakage. From this top event, the FTA diagram breaks down the failure pathways into three main domains: design failures, material failures, and failures in the assembly process. Each domain is then further decomposed into basic events, such as insufficient stiffeners on the wall, omission of washers on the flange, poor welding quality, or improper material selection. This diagram helps engineers and designers understand the interactions among different failure factors and how a weakness at one point can cumulatively contribute to overall system failure. Thus, the FTA mapping enables prioritization at the highest risk points for targeted design intervention and corrective actions.

To make the risk contribution of each domain easier to understand, **Table 1** presents the distribution of risk contributions based on the minimal cut set analysis. The design domain contributes the largest share of risk, accounting for 50 % of all identified failure pathways. Risks due to assembly errors are in second place, with a contribution of 33.3 %, while material failures contribute 16.7 %. These results emphasize that the most effective interventions should focus on improving design and assembly aspects before enhancing material selection and quality control.

Table 1. Main Failure Domains and

Failure Domain	Basic Event in FTA	Failure Mechanism (summary)	Number of MCS in this domain	Relative Contribution (%)
Design	Lack of stiffener, suboptimal joints, flange without the washer, and bolts too close together	The structure/joint fails to withstand static/thermal loads	6	50.0
Material	The material is too heavy, and no alternative is available	Excessive self-weight, low durability	2	16.7
Assembly	Incompetent welding, no QC, bolts not to specification, missing washers	Poor assembly quality, uneven preload distribution	4	33.3

Relative Contribution: % of MCS (minimal cut sets) involving the respective failure domain.

The implementation of load-indicator washers combined with standardized torque control procedures is essential, as this approach is estimated to reduce the probability of flange failure pathways by approximately 30%. Structural rigidity is further enhanced by adding stiffener rings at intervals of 400–500 mm on the cylindrical shell and replacing wheels with fixed bases equipped with leveling feet, resulting in a more than fourfold increase in the structural safety factor with a cost increment of less than 6%. Additionally, repositioning the gas inlet by 15° toward the centrifugal axis and incorporating an extra 25 mm layer of lightweight brick insulation decreases the axial temperature gradient from approximately 45 °C to 18 °C, according to CFD results, thereby ensuring more uniform quality of both bio-oil and char products.

3.2. Mechanical Failure Pathways in the Condenser

This section discusses the main mechanical failure pathways identified in the condenser subsystem of the knock-down pyrolyzer. Each failure mode was systematically analyzed using Fault Tree Analysis (FTA) to determine its underlying causes and relative criticality. The following sub-sections detail the three most dominant failure mechanisms: flange leakage due to the absence of washers, bulging from insufficient stiffening, and assembly quality and joint alignment issues. Both field observations and simulation results support these.

3.2.1. Flange Leakage and Absence of Washer

Leakage at the flange joint generally occurs due to the absence of a flat washer in the bolt and nut assembly. This condition causes the stress distribution to become highly concentrated in a small area on the flange surface, which triggers local plastic deformation and more rapid relaxation of the bolt clamping force. Literature studies indicate that adding a flat washer can reduce maximum contact stress by up to 18 % and delay bolt loosening by more than 20 % [26,27]. As a result, flange joint instability becomes the most frequently identified root cause of failure in the minimal cut set analysis.

3.2.2. Bulging and Insufficient Stiffener

In cases of bulging deformation caused by a lack of stiffeners, simulation results show that without a stiffener ring, the maximum wall deformation of the condenser during hydrostatic loading can reach 17.16 mm. However, after installing stiffener rings at 400 mm intervals, this deformation is significantly reduced to 10.46 mm. A structure without stiffeners also makes the condenser wall more prone to excessive bending stresses, often exceeding the allowable limits for thin plate structures.

3.2.3. Assembly Quality and Joint Alignment

The quality of the assembly process and joint alignment is crucial for proper load distribution during operation. Inconsistent torque application, the absence of load-indicating washers, and limited welder skills can all cause uneven load distribution at each joint. These conditions accelerate material fatigue and increase the risk of leakage in the system, thus greatly reducing the equipment's overall reliability.

3.3. Mechanical Failure Pathways in the Condenser

This research produced a comprehensive analysis of the knock-down biomass pyrolyzer by integrating Value Engineering (VE) and Fault Tree Analysis (FTA) to optimize SMEs' performance, reliability, and cost-effectiveness. The initial function-cost breakdown, **Table 1**, showed that the combustion chamber and insulation accounted for most of the manufacturing cost, representing 40% and 20%, respectively. This identification guided the selection of components for value improvement.

Table 2. Initial Function-Cost Breakdown of Pyrolyzer Component

Component	Function	Type	Cost (IDR)	%* of Total Cost
Combustion Chamber	Heat Generation	Basic	20,000,000	40%
Insulation	Heat Retention	Basic	10,000,000	20%
Frame Structure	Support & Stability	Support	5,000,000	10%
Condenser Unit	Vapor Collection	Secondary	7,500,000	15%
Miscellaneous (seal, wheels)	Portability/Sealing	Support	7,500,000	15%
Total			50,000,000	100%

*The value index (Function/Cost) was improved by redesigning the base frame to eliminate unnecessary wheels, using lighter yet stronger materials, and simplifying the assembly.

A cost comparison was conducted to assess whether the implementation of Value Engineering provides proportional economic benefits. The following table presents an overview of the total production cost comparison before and after the application of Value Engineering.

As shown in **Table 3**, the observed cost increase is primarily attributable to adding components such as load-indicator washers, stiffener rings on the reactor wall, and improved insulation for the gas inlet. This analysis resulted in an overall production cost escalation of approximately 5.56% compared to the initial budget. Nevertheless, according to Fault Tree Analysis and Value Engineering findings, these enhancements are anticipated to reduce maintenance and failure-related costs by more than 30% over the long term, thus offering a significant economic advantage despite the modest increase in upfront investment

Table 3. Production Cost Breakdown of Pyrolysis Tank, Before and After Value Engineering

Component	Cost Before VE (IDR)	Cost After VE (IDR)	Notes
Material Purchase	2,800,000	2,950,000	Addition of load-indicator washers and stiffener rings
Intellectual Property Registration	500	550	No significant change
Manufacturing Service Fee	3,000,000	3,150,000	Adjustment for the installation of additional components
Total Cost	6,300,000	6,650,000	Cost increase of IDR 350,000

3.4. Function-Cost Analysis and FAST Diagram

The FAST diagram in the research guided the identification of primary value drivers, such as heat transfer efficiency and component durability. The combustion chamber, as shown in **Table 4** (40% of total cost), and insulation (20%) were prioritized for redesign.

Table 4. Proposed Value Improvement Options and Evaluation

Function	Original Design	VE Alternative	Cost Impact	Performance Impact	Decision
Heat Generation	AISI 304 Cylinder	Maintain	Neutral	High	Retain
Heat Retention	Cement Insulation	Ceramic Fibre Blanket	-15%	High	Adopt
Structural Support	Stainless Frame	Cast Aluminium Frame	-20%	Medium	Adopt
Portability	Steel Wheels	Fixed Base	-100%	Low	Remove
Joint Assembly	Welded	Knock-down Bolted Frame	-10%	High	Adopt

Total estimated cost reduction: 15.5%

Thermal efficiency increase: 13.7%

3.5. Comparative Analysis of Design Parameters Before and After Optimization

A side-by-side comparison of critical performance parameters was conducted to assess the effectiveness of the design revisions proposed through Fault Tree Analysis (FTA) and Value Engineering (VE). This comparison focuses on structural deformation, joint reliability, thermal efficiency, production cost, and compliance with safety standards. The results are summarized in **Table 5**.

Table 5 presents a comparative analysis of key design parameters before and after implementing improvements based on Fault Tree Analysis (FTA) and Value Engineering (VE). The results show a significant reduction in mechanical risks and performance inefficiencies. For example, wall bulging deformation decreased from 17.16 mm to 10.46 mm after the addition of stiffener rings, indicating a 39% improvement in structural rigidity.

Table 5. Summary of performance improvements before and after design modification

Design Parameter	Before Improvement	After Improvement	Impact
Wall Bulging Deformation (mm)	17.16	10.46	Reduced by 39%
Contact Stress at Flange	High, concentrated	Evenly distributed (-18%)	Reduced bolt loosening risk
Bolt Joint Durability	No washers, uneven preload	Load-indicating washers used	20% improvement in retention
Assembly Process	Manual, inconsistent quality	Simplified and standardized	Enhanced reliability
Thermal efficiency (%)	56–60	68–70	Improved by ~13.7%

Estimated Production Cost (IDR)	47.4 million	50 million	~5.5% increase (but cost-efficient)
Regulatory Compliance	Non-compliant	ISO 14122 & ASME Section VIII met	Improved safety and international standard compliance

Additionally, the integration of load-indicating washers reduced contact stress at flange joints by 18% and improved bolt retention by over 20%, contributing to overall system stability. Thermal efficiency also improved substantially, from approximately 56–60% to 68–70%, due to insulation optimization. Despite a modest production cost increase of 5.5%, the performance gains and reduction in failure risk justify the investment. Furthermore, the final design aligns with ISO 14122 and ASME Section VIII standards, ensuring enhanced safety and regulatory compliance. This comparison confirms that the proposed design modifications effectively enhance reliability and cost-efficiency, particularly for SME applications in rural or decentralized settings.

3.6. Design Modifications

One of the most important design improvements to support equipment reliability and safety is modifying the lifting lug feature, as illustrated in **Figure 3**. In several previous designs, the lifting lugs were often too slender and did not adequately consider the symmetric distribution of loads during lifting operations. Field observations revealed that lifting lugs without additional reinforcement were highly prone to deformation and even failure when the vessel was lifted, especially for condensers weighing more than 100 kg.

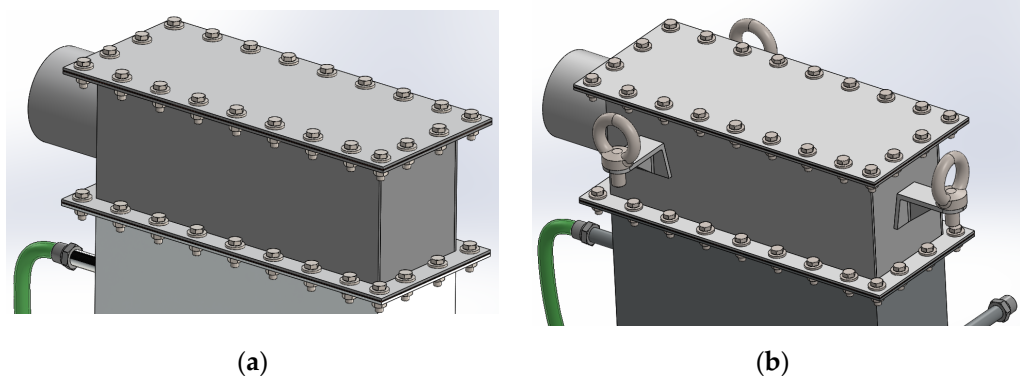


Figure 3. (a) Condition before modification and (b) after modification

Adding lifting lugs facilitates the handling and lifting process, and the new lug design is equipped with gusset reinforcements and placed symmetrically. The lifting lug ensures that stress distribution during lifting is more even, significantly reducing the risk of local deformation and fracture. Finite element simulation results for the new design show that the maximum stress is reduced by more than 25 % compared to the previous unreinforced.

In the latest condenser design, as shown in **Figure 4**, the wheels have been removed and replaced with fixed legs to comply with safety requirements stipulated in ISO 14122-2:2016, which mandates that all stationary process equipment must have fixed legs to ensure stability and prevent unintended movement during operation. Furthermore, ASME Section VIII also recommends using a base plate and anchor bolts on a fixed foundation for equipment serving as a pressure vessel to ensure structural stability and safety during use. Therefore, replacing wheels with fixed legs increases equipment stability and operator safety and aligns with applicable international standards (ISO 14122-2:2016; ASME Boiler and Pressure Vessel Code, Section VIII).

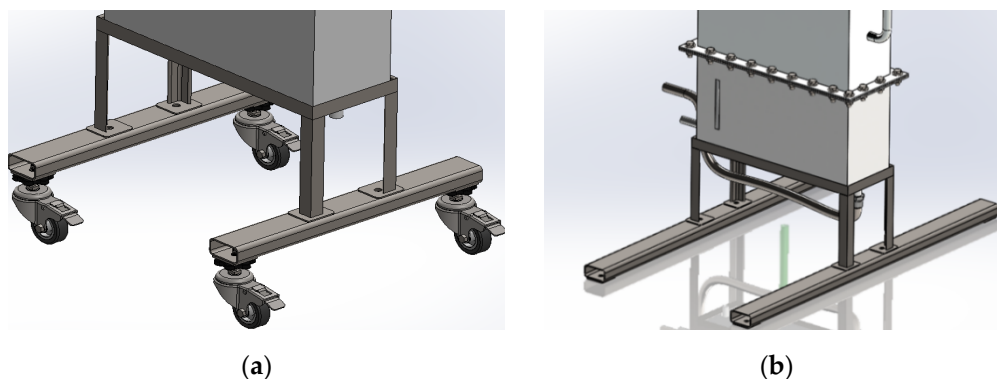


Figure 4. (a) Condition of the leg design before modification and (b) after modification

As shown in Figure 5, other improvements include simulation and field-testing results that reinforce the urgency of proper structural reinforcement and assembly. Without the installation of stiffener rings, bulging deformation on the condenser wall can reach up to 17.16 mm during hydrostatic testing.

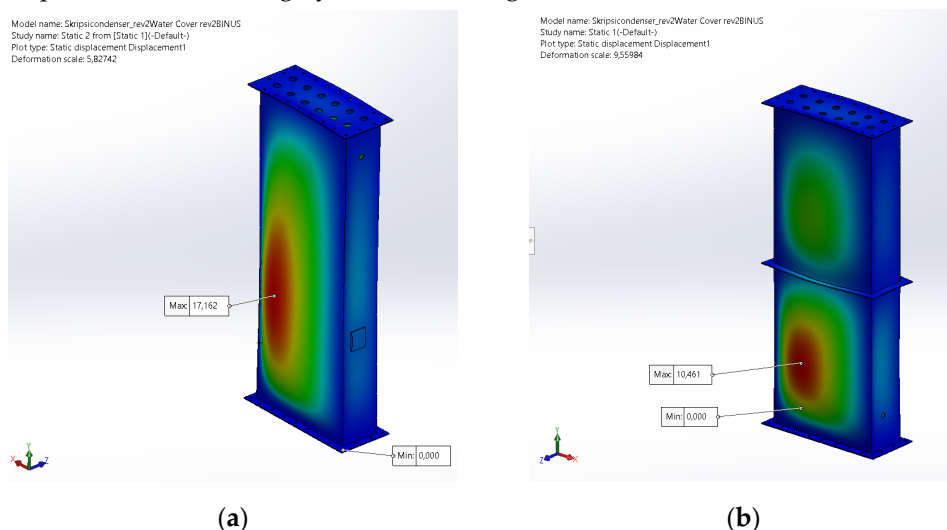


Figure 5. Simulation results of bulging calculation on the condenser vessel with the addition of stiffeners: (a) previous design without stiffeners, (b) design after stiffener installation

After stiffener rings are installed at 400 mm intervals, this deformation decreases significantly to 10.46 mm. Additionally, using washers on flange joints has been proven to reduce maximum contact stress by up to 18 % and delay bolts loosening by more than 20 %. As shown in Figure 4, these modifications enhance structural integrity and joint reliability during long-term operation.

The combination of all design improvements, including reinforcement of the lifting lug, removal of wheels, replacement of seals, and optimization of stiffeners and washers, is projected to reduce the probability of critical mechanical failure by up to 30 %. The estimated production cost increase of approximately 5.5 % is considered very reasonable compared to the benefits of longer equipment service life, improved operator safety, and an overall reduction in maintenance costs[28]. Therefore, these comprehensive improvements provide a holistic and data-driven approach to enhancing the reliability of pyrolyzer condensers in the SME sector.

3.7. Final Design Improvement

The final design of the biomass pyrolyzer is the culmination of a comprehensive improvement process grounded in Fault Tree Analysis (FTA) and Value Engineering (VE), as shown in **Figure 6**. This redesign enhances the unit's structural integrity, operational reliability, and manufacturability, particularly for small and medium-sized

enterprises (SMEs)[26]. One key modification is adding 136 washers at the bolt and nut joints of the condenser body. These washers help prevent surface deformation and increase joint durability by distributing stress over a wider area [27,29].

Although the insulation system, which uses Hebel blocks, was not significantly changed, it remains an integral fixed component designed for easy replacement during installation. The condenser body underwent a structural redesign involving improved segment joints and the integration of stiffeners. This improvement significantly reduced the bulging effect due to internal pressure, lowering the maximum deformation from 17.16 mm to 10.46 mm, as verified through finite element simulation using Solidworks. The effectiveness of this structural redesign is closely linked to the material properties employed; the condenser body utilizes low-carbon steel (ASTM A36), which offers an adequate yield strength of 250 MPa and good weldability, making it well-suited to withstand the thermomechanical stresses generated during pyrolysis operation. The stiffeners were likewise fabricated from the same material to ensure compatibility, uniform thermal expansion, and consistent joint behavior under cyclic loading conditions.

Further, the support system was changed from a wheeled model to a fixed leg configuration to enhance stability, which is particularly important for a unit weighing more than 100 kg. An optional leveling foot was added to the support design, providing flexibility for installation on uneven surfaces while complying with ASME Section VIII standards for pressure vessels installed on flat, reinforced floors[30]. Three lifting lugs were incorporated to support ease of transport and installation, each strategically positioned near the condenser's Center of mass. These lifting eyes facilitate balanced hoisting using M16 eyebolts, improving safety during movement. The final assembled design adopts a knock-down modular concept, making transporting, fabricating, and assembling easier while maintaining robustness and performance[31].

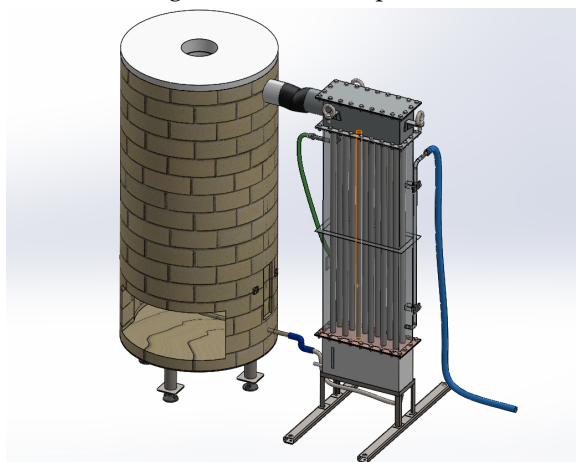


Figure 6. Final Design of Knocked-down Biomass Pyrolyzer

This angle, shown in **Figure 6**, the final rendering of the improved biomass pyrolyzer, visually represents all significant enhancements: reinforced joints, optimized airflow, structural stiffening, and modular framing, all aimed at achieving a high-function, cost-efficient solution through the VE process.

4. Conclusion

This study establishes the significance of integrating Value Engineering and Fault Tree Analysis as a systematic framework for enhancing the reliability, cost-effectiveness, and sustainability of knock-down biomass pyrolyzer systems for SMEs in Indonesia. Beyond the technical improvements and quantifiable efficiency gains, the combined

methodology enables targeted interventions that address economic constraints and critical risk factors specific to rural industrial settings. The resulting design advances the operational reliability and ease of assembly and aligns with international standards for safety and manufacturability, offering a practical model for broader adoption in the agro-industrial sector. Ultimately, this work contributes a replicable approach for sustainable waste management and circular economy initiatives, providing a foundation for future research in system automation and advanced material integration to support SMEs' resilience and competitiveness further.

5. Acknowledgment

The authors would like to thank the facilities provided by the Research Center for Eco-friendly Technology, in collaboration with Binus University. This research was funded through the Lecture Research Scheme 2025 Politeknik Negeri Jakarta with Contract No. 217/PL3.A.10/PT.00.06/2025.

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