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Article

Alternative Design and Development of Material Handling Platform

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Abstract. In a world where efficiency and sustainability in logistics are increasingly significant, innovative load-carrying solutions are essential. This study investigates the mechanical performance of a conventional plastic pallet compared to a newly proposed P-Sling design using Finite Element Analysis (FEA). FEA serves as a powerful tool to simulate real-world conditions, enabling accurate predictions of stress, deformation, and structural reliability. Initial results show that the original P-Sling design exhibits higher displacement and stress, which aligns with its intended flexibility for dynamic use. In contrast, the plastic pallet, designed as a rigid structure, displays only minor bending but may be prone to failure under prolonged stress. To further enhance the P-Sling's performance, its base thickness is increased from 1 mm to 10 mm, significantly reducing stress and deformation while maintaining its flexible nature. Although the plastic pallet maintains greater rigidity, the improved P-Sling presents a promising and adaptable alternative, particularly in environments that require both flexibility and strength under dynamic loads. This study addresses an important gap by applying Finite Element Analysis (FEA) to the P-Sling design, offering new insights into optimizing the performance of flexible load-bearing structures in changing conditions.

Keywords: Product design and development, user-centric design, P-Sling, finite element analysis, material handling.

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1. Introduction

In modern engineering, the ability to predict and analyze the behavior of structures and materials before physical implementation is essential. Advanced computational tools have transformed this process, with Finite Element Analysis (FEA) emerging as one of the most widely used techniques [1]. FEA plays a key role in the design and optimization of components ranging from simple mechanical parts to large-scale structures, supporting safety, efficiency, and innovation across various industries. It is commonly used to simulate real-world scenarios, allowing engineers to assess how structural elements and materials perform under different conditions [2]. By accurately modeling these responses, FEA provides valuable insights into performance while reducing the need for extensive physical testing. This not only speeds up the design process but also lowers costs and resource use, making FEA a vital tool in engineering and material science.

In logistics, warehouses, stores, and many other places, a wide range of devices are employed to assist with the carrying and transportation of items. Devices such as pallets and bags play a crucial role in streamlining these processes [3], [4]. Pallets, for instance, provide a stable and sturdy platform for stacking goods, making it easier to move large quantities of items at once. This capability allows for the transportation of products in batches, significantly enhancing efficiency and organization within the workflow. Similarly, bags offer a flexible solution for carrying smaller items or irregularly shaped products, ensuring that they can be transported securely and conveniently. These assistive devices not only simplify the transportation process but also enable the use of various vehicles and carrying platforms, which further reduces the reliance on manual labor. Forklifts and pallet jacks, for example, can easily lift and move loaded pallets, minimizing the physical strain on workers and speeding up the transfer of goods. By reducing the need for excessive manual handling, these tools contribute to a safer and more ergonomic working environment. Overall, the use of such carrying devices is essential in modern logistics and inventory management, as they enhance productivity, safety, and efficiency across various settings.

While traditional pallets are well-studied and widely used, the newly proposed P-Sling design remains relatively unexplored in terms of structural analysis. No Finite Element Analysis has been conducted on the P-Sling to date, leaving its mechanical behavior under load largely unknown. In particular, its stress distribution, displacement patterns, and ability to withstand real-world loading conditions have yet to be validated. Moreover, there is limited understanding of how the P-Sling's performance compares to that of standard plastic pallets, especially in terms of durability, flexibility, and load-bearing efficiency. This lack of data presents a critical gap in evaluating its feasibility for practical use in dynamic material handling environments.

In 2024, Rianmora et al. [5] introduced a new design for the P-Sling, aiming to challenge traditional plastic pallets with innovative features. This design promises to revolutionize material handling by offering flexibility, strength, and space-saving attributes. The research focuses on creating a user-friendly platform for loading and unloading sago bags, incorporating principles of product design and development. The new P-Sling features ergonomic handles and durable materials, enhancing functionality and efficiency. This platform offers an alternative approach to reducing costs and materials used in creating heavy-duty material handling platforms, while maintaining the quality of the carrying activity.

This research proposes a detailed study of the new P-Sling design using Finite Element Analysis (FEA). The P-Sling's ability to withstand and respond to various load conditions is meticulously analyzed through FEA, providing insights that physical testing alone might miss. The full potential and limitations of the P-Sling are aimed to be uncovered, demonstrating its performance under different stress scenarios. This comprehensive evaluation not only highlights the practical applications and performance of the P-Sling compared to traditional plastic pallets but also provides valuable data that could guide future improvements and innovations in material handling solutions. Furthermore, a thorough comparison will be performed with the traditional plastic pallet, known for its solid rigidity and durability. This side-by-side evaluation will not only expose performance differences but also highlight the unique benefits and potential trade-offs of the P-Sling. By comparing these two designs, the aim is to provide a clear and insightful understanding of their practical uses, durability, and efficiency. The study aims to deliver ground-breaking insights that could lead to a new era of material handling solutions, offering the industry more efficient, cost-effective, and adaptable options. The results could potentially reshape the future landscape of material handling equipment, setting a new benchmark for innovation and functionality.

2. Related Works

2.1. Material Consideration

The choice of material significantly affects characteristics such as durability, weight, strength, and overall usability [6]. Therefore, selecting an appropriate material requires careful evaluation of several key criteria to ensure the product meets desired specifications and performance standards. Cost-effectiveness is a primary consideration, involving not only the initial cost but also long-term economic implications like maintenance, replacement costs, and potential savings from increased efficiency or extended product lifespan [7]. Balancing cost with performance ensures the product is economically viable and competitive. Functional performance is also critical. The chosen material must withstand operational stresses and environmental conditions throughout its lifecycle. This includes evaluating mechanical properties like tensile strength, elasticity, and hardness, as well as resistance to factors such as corrosion, temperature extremes, and UV exposure [8], [9]. Selecting materials that perform well under expected conditions ensures reliability and longevity. Environmental impact is increasingly important, driven by sustainability and eco-friendly practices [10]. This involves assessing the environmental footprint of the material from extraction and processing to disposal or recycling. Renewable, recyclable, or lower-impact materials are preferred to reduce the product's overall ecological footprint. For the key point, material selection is a complex decision-making process that balances cost, performance, and environmental factors. By carefully evaluating these aspects, designers can create functional, durable, and sustainable products.

2.2. Pallet and P-Sling Consideration

Plastic pallets and P-Slings are widely used across various industries, each offering distinct benefits suited to different applications. Plastic pallets, typically manufactured from polypropylene or polyethylene, are prized for their rigid and robust structure, making them ideal for heavy-duty tasks [11]. These pallets provide excellent durability and can withstand significant loads, which justifies their moderate cost, even though they are more expensive than P-Slings. Their widespread use in logistics, warehousing, and shipping industries underscores their reliability and effectiveness in handling and transporting goods securely [5].

In contrast, P-Slings are crafted from polyester, providing a unique blend of flexibility and strength. This combination makes them suitable for specific industry applications where adaptability and space-saving are important. P-Slings are notably lightweight and foldable, allowing for efficient storage and transportation as they occupy minimal space when not in use. Their design makes them an excellent choice for operations where frequent handling and compact storage are necessary. Additionally, P-Slings are more affordable than plastic pallets, offering a cost-effective solution without compromising on strength and durability. Their economical nature and versatile applications make them an attractive option for industries looking to optimize their material handling processes while managing costs effectively [5].

2.3. Polyester Fabric

Polyester, a widely used polymer, has become increasingly popular in fabric industries due to its unique properties [12]. Polyester fabrics are known for their excellent mechanical characteristics, good resiliency, chemical inertness, and heat resistance, making them durable and versatile for various applications [13]. The structure of polyester fabric also contributes to its performance. Increasing the number of filaments in a yarn increases the surface area of the fibers and reduces the spaces between them, providing water repellence due to surface tension. At the same time, the space between fabric filament is big enough to remain breathable and allow moisture to breath away from the body, making it suitable for activewear and outdoor clothing. Additionally, the higher the filament density, the stronger the fabric becomes, further enhancing its strength and durability [14].

2.4. Polypropylene

Polypropylene (PP) is a thermoplastic with the lowest density among commodity thermoplastic plastics. Known for its excellent chemical resistance, polypropylene can be processed through various converting methods such as injection molding and extrusion, which makes it highly versatile for different applications. One significant advantage of polypropylene is its high temperature resistance, making it particularly suitable for items that require frequent sterilization, such as trays, funnels, pails, bottles, carboys, and instrument jars commonly used in clinical environments. Polypropylene's crystalline structure imparts a high level of stiffness and a relatively high melting point compared to other commercial thermoplastics, resulting in excellent physical, mechanical, and thermal properties at room temperature. However, polypropylene is not suitable for use at temperatures below 0°C, as its performance deteriorates in colder conditions. Despite this limitation, polypropylene remains a valuable industrial petrochemical used in the production of various chemical derivatives. Its combination of low density, chemical resistance, high temperature tolerance, and strong mechanical properties underscores its importance in the manufacturing of numerous products, particularly those that require frequent sterilization, and highlights its fundamental role in industrial applications [15].

2.5. Finite Element Analysis

Finite Element Analysis (FEA) is a powerful computational tool that empowers designers to simulate and analyze complex structures with a high degree of accuracy. This method involves discretizing intricate geometries into smaller, manageable elements, enabling detailed examination of how structures respond to various forces and conditions. By breaking down complicated geometries, FEA provides a comprehensive understanding of stress, strain, and deformation characteristics under different load scenarios [16], [17]. The simulation capabilities of FEA are extensive, allowing for the thorough analysis of a design model's performance.

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These simulations consider material properties, structural geometry, and applied loads to provide insights into potential failure points and overall behavior [18]. By accurately predicting real-world performance, FEA helps engineers optimize designs for strength, durability, and efficiency before creating physical prototypes, thus saving time and resources. FEA's ability to model complex interactions within a structure is invaluable in the design and development process. It reduces the need for extensive physical testing, enhancing both the safety and reliability of the final product. Through iterative simulations, designers can explore a wide range of scenarios and design variations, identifying the best possible configuration for specific applications. In summary, *Finite Element Analysis (FEA)* is essential in modern engineering, offering a detailed and accurate method for evaluating the structural integrity and performance of complex designs. Its role in simulating real-world conditions and analyzing various factors makes it indispensable for optimizing product designs and ensuring their practical success.

Finite Element Analysis (FEA) comprises three primary steps: pre-processing, solution, and post-processing, as illustrated in Fig. 1. The pre-processing phase involves model designing, creating a 3D model, and determining the material properties. This step sets the foundation for accurate simulation by defining the physical characteristics and geometry of the model. The solution phase follows, where loads and other constraints are applied to the simulation. This includes creating meshes and nodes to discretize the model and running the simulation to compute the response of the model under the specified conditions. Finally, the post-processing phase involves analyzing the simulation results, which include stress plots and displacement plots. Additionally, simulated animations can be generated from the results, providing a visual representation that aids in better understanding [16].

SOLIDWORKS Simulation is an essential tool in software, which is used for Finite Element Analysis. It provides an easy-to-use portfolio for structural analysis and provides engineers with a wide range of tools to conduct virtual experiments, improve designs, and enhance performance. With its user-friendly interface and powerful capabilities, engineers can simulate real-world situations accurately from the CAD model, gaining valuable insights into their designs' behavior [19].

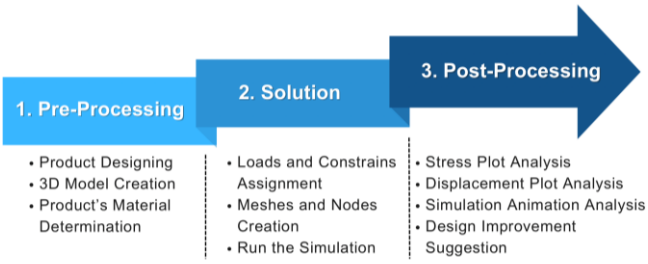

Fig. 1. Overview of finite element analysis adapted from [16].

2.6. Fault Tree Analysis

Fault Tree Analysis (FTA) is one of the most popular failure analysis techniques [20]. It is conducted to simplify system failures into a single diagram. In this analysis, all possible causes of failure are systematically placed on a chart in the correct sequence. These failures are connected through "AND/OR" gates, indicating whether particular events need to occur together or independently to trigger subsequent events [21]. This analysis identifies the causes that lead to system or component failures, allowing decision-makers to take preventive actions and improve the system's risk level. Fault Tree Analysis (FEA) is presented in a top-down approach that shows the relationships from system failure to its root causes [20].

3. Research Methodology

3.1. Product Design and Development on "P-Sling" Design

According to the recent work proposed by Rianmora et al. in 2024 [5], the design of the "P-Sling" has been introduced based on comments and requirements from target customers, with product design and development (PDD) applied as the key tool. To establish a systematic framework for the research, four main sequences (Fig. 2) are essential. The process begins with a thorough Customer Satisfaction Analysis, aimed at understanding customer needs and translating them into key engineering design factors, forming the foundation of the entire design process. Following these insights, the Conceptual Design stage drafts the desired product design. In the System Level Design step, this drafted design is classified into main and sub-components, ensuring a structured approach. Next, Detailed Design specifies key findings and requirements for each component, aligning them with customer needs and functional requirements. Finally, the *Testing* and *Refinement* stage, illustrated through case studies, evaluates material properties for components like the 'Pallet' and 'P-Sling,' ensuring the product meets quality standards and customer expectations.

The key point for the design stage is how to extract customer requirements and translate them into the design, where the obtained results can introduce several user-centric improvements. As shown in Fig. 3 and Table 1, this ensures both comfort and efficiency in use. The handle features a rubber grip for enhanced comfort during handling, addressing ergonomic concerns that are often overlooked in traditional designs. Additionally, the side belt, crafted from 1.5 mm thick polyester, is designed to accommodate both 50% and 100% capacity, offering flexibility for different loading needs.

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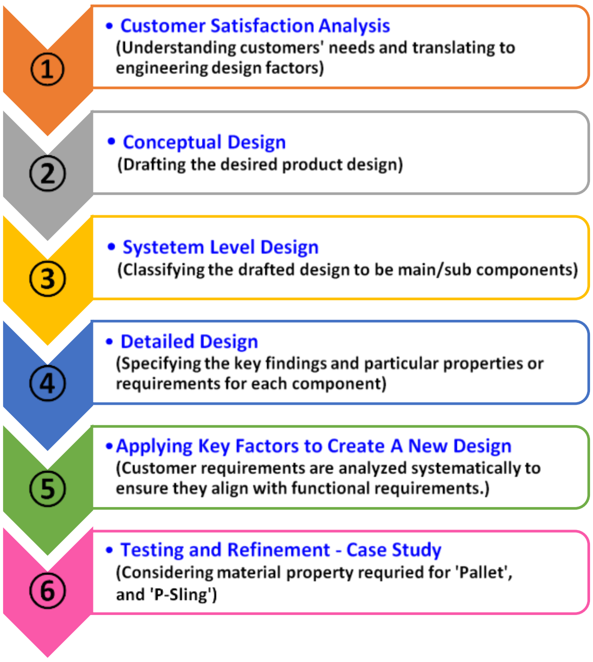

Fig. 2. The summarized flowchart for the overall sequences of the research [5].

This adaptability makes it suitable for various operational scenarios, from light to heavy loads. The base of the P-Sling, constructed from 1 mm thick polypropylene (PP), measures 109 x 120 cm, ensuring a robust and efficient solution that can withstand rigorous use.

This combination of materials and thoughtful design elements, central to the principles of product design and development, underscores the potential of the new P-Sling to provide a more versatile and reliable option for material handling, potentially revolutionizing the industry with its innovative approach.

However, it is better to check the force distribution around the area of interest using simulation forecasting before attempting real production. This approach allows design engineers or the design team to anticipate unexpected situations that might occur during real-time use. Therefore, finite element analysis (FEA) has been applied in this study to forecast trends and deformations that might occur and to assess the safety conditions of the design for further improvement.

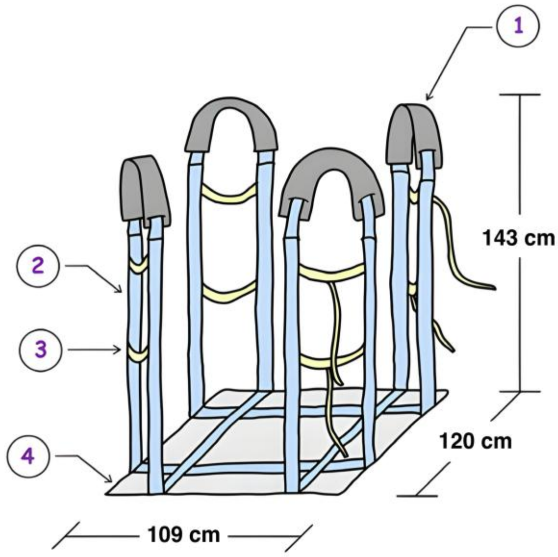

Fig. 3. P-Sling design [5].

Table 1. Components and description of proposed design.

No.	Components	Description
①	Handle	Rubber Handle
②	Side belt	Material: Polyester Thickness: 1.5 mm
③	Horizontally Adjustable Belt	Designed for 50% and 100% capacity
④	Base	Material: Polypropylene (PP) Thickness: 1 mm Size: 109 x 120 cm

3.2. P-Sling Modelling Parameter

In order to conduct the finite element analysis, the initial step involves constructing a 3D model of the design. In this study, the model, shown in Fig. 4., is created using SOLIDWORKS software. Following the development of the 3D model, materials are assigned to the components. The material properties table is shown in Table 2 [22]. In the case of this design, polypropylene copolymer is designated for the base of the P-Sling, while polyester fabric is utilized for other components, which are the side belts and the horizontal belts.

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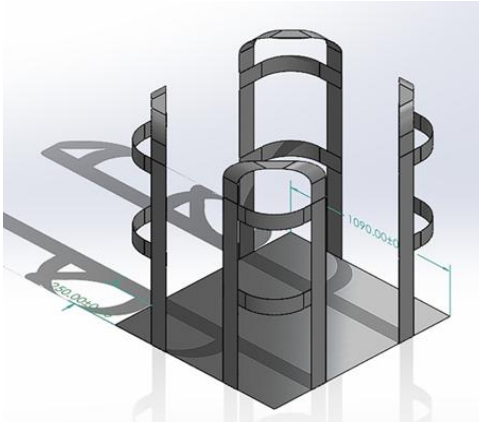


Fig. 4. 3D model of the suggested P-Sling design.

Table 2. P-Sling Material Properties.

Material Properties	Polypropylene Copolymer	Polyester Fabric Reinforcement
Elastic Modulus	4930 – 899000 psi	653000 psi
Compressive Strength	4000 – 16000 psi	65300 psi
Tensile Strength	1230 - 16000 psi	19600 psi
Flexural Strength	1950 - 26300 psi	21800 psi
Mass Density	0.0282 - 0.100 lb/in³	0.0488 lb/in³

3.3. Plastic Pallet Modelling

For the plastic pallet model, the initial step involves obtaining a 3D CAD model from an online source. The obtained 3D model is shown in Fig. 5. Subsequently, the model is assigned a material of high-density polyethylene, which has the property shown in Table 3 [23]. In preparation for simulation, a fixture point must be specified, denoting the contact region where the forklift fork interfaces during handling. To define this area, a 0.1 mm thin sketch is applied to the bottom of the pallet at the contact region.

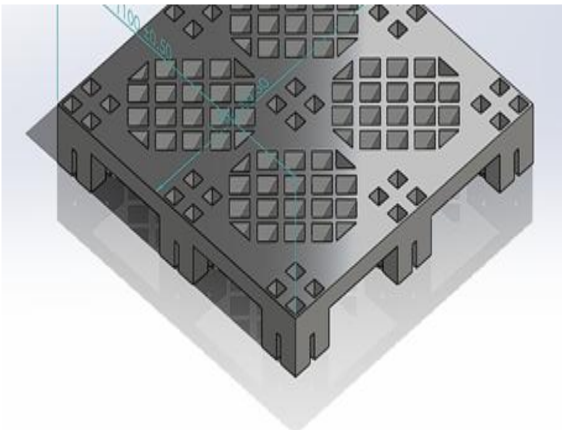


Fig. 5. 3D model of plastic pallet.

Table 3. P-Sling material properties.

Material Properties	High Density Polyethylene
Elastic Modulus	81900 - 218000 psi
Compressive Strength	580 - 3340 psi
Tensile Strength	1600 - 6240 psi
Flexural Strength	2000 - 7000 psi
Mass Density	0.0334 - 0.0359 lb/in³

3.4. Simulation

After constructing the 3D models of the P-Sling and the plastic pallet, a comprehensive Finite Element Analysis is conducted to assess their structural responses under realistic loading conditions. The simulation process begins with defining the interactions between each component in the assembly. This step is essential for guiding the software in understanding how parts behave when in contact, whether they are bonded, in contact, or allowed to move freely with respect to each other. Accurately modeling these relationships ensures that stress and displacement are distributed realistically throughout the structure. The next step involves assigning fixation points, which are specific areas of the model that are constrained from movement. For both the P-Sling and the plastic pallet, these fixed points are located at the regions that rest on the forklift forks. During actual lifting operations, these points remain stationary and therefore serve as critical references for understanding how the rest of the structure deforms under load. Once the constraints are defined, external forces are applied to simulate the operational environment. These forces include the effect of gravity, set at 9.81 meters per second squared, and a uniformly distributed load that represents the weight of stacked sago bags. These loads are applied across the top surface of each platform to replicate real-world use as closely as possible.

Before running the simulation, the software automatically performs a meshing process that divides the 3D geometry into many smaller triangular elements. This step is important for enabling the program to solve structural equations within each small segment, especially when analyzing complex shapes. After the setup is complete, the Finite Element Analysis simulation is executed to produce detailed results showing how each design behaves under stress. These results include visual representations of displacement, stress distribution, and potential failure points. The analysis offers valuable insights into the mechanical performance and durability of the P-Sling in comparison to the traditional plastic pallet, providing a strong foundation for evaluating its practical use and identifying possible improvements for future development.

4. Result and Discussion

4.1. Finite Element Analysis

This study explores the application of Finite Element Analysis (FEA) to optimize the design and development of material handling platforms, specifically focusing on pallets and P-Slings comparison. By utilizing FEA, the research aims to enhance the structural integrity, durability, and efficiency of these platforms. The analysis includes:

- *Structural Integrity*: Evaluating the load-bearing capacity and stress distribution to ensure safety and reliability under various operational conditions.
- *Material Optimization*: Identifying the most suitable materials and their configurations to reduce weight while maintaining strength and durability.
- *Design Enhancements*: Proposing design modifications based on FEA results to improve performance, such as ergonomic features for ease of handling and space-saving capabilities.
- *Cost Efficiency*: Analyzing the cost implications of different design choices and materials to find the most economical solutions without compromising quality.

Finite Element Analysis (FEA) for simulating plastic materials or polymers presents several challenges and difficulties:

- *Non-linear Material Properties*: Plastics and polymers exhibit non-linear stress-strain behavior, which complicates the simulation process. Capturing the accurate response of these materials under different loading conditions requires advanced material models and can be computationally intensive.
- *Viscoelastic and Viscoplastic Behavior*: Many polymers demonstrate time-dependent behavior, such as creep and stress relaxation. Incorporating viscoelastic or viscoplastic properties into FEA models adds complexity and requires detailed material characterization data.
- *Temperature Sensitivity*: The mechanical properties of plastics can vary significantly with temperature. Simulating the effects of temperature changes, including thermal expansion and softening, necessitates coupled thermo-mechanical analysis, increasing the model's complexity.
- *Large Deformations*: Plastics can undergo large deformations before failure, necessitating non-linear geometric analysis in FEA. This requires careful meshing and computational resources to maintain accuracy and stability in the simulation.
- *Material Anisotropy*: Some polymers exhibit anisotropic behavior due to their manufacturing processes, such as injection molding. Accurately modeling anisotropic properties requires detailed knowledge of the material's internal structure and orientation.
- *Complex Failure Mechanisms*: Predicting the failure of plastic materials involves understanding various failure modes, such as brittle fracture, ductile yielding, and fatigue. Incorporating these mechanisms into FEA models is challenging and often requires extensive experimental validation.
- *Computational Resources*: Simulating plastic materials with high fidelity requires significant computational resources, including memory and processing power, which can limit the feasibility of detailed models for large or complex structures.

Moreover, addressing these challenges requires a combination of advanced material models, extensive experimental data for material characterization, and significant computational resources to ensure accurate and reliable FEA simulations of plastic materials and polymers.

4.2. Experiment on FEA

The findings aim to provide actionable insights for manufacturers and designers in the material handling industry, ensuring that the platforms meet both functional and economic requirements.

For the virtual experiment in this study, FEA simulations were conducted to provide a comprehensive comparison of the load-handling performance between the newly suggested P-Sling design and the conventional plastic pallet. Tables 4, 5, 6 and 7 present detailed finite element simulation results, showcasing the performance differences between a standard HDPE plastic pallet and the proposed P-Sling design. These simulations applied loads of 1250 kg, representing a typical weight scenario for sago bag carrying applications, and 2000 kg, representing an overweight condition.

The results indicate that, under a load of 1250 kg, the plastic pallet exhibits a maximum displacement of 1.431 mm. This relatively small displacement suggests that the plastic pallet maintains its structural integrity well under the applied load.

Conversely, the P-Sling design shows a significantly higher maximum displacement of 784.4 mm, highlighting its reduced effectiveness in maintaining shape and structural integrity under heavy loads. When the load is increased to 2000 kg, the plastic pallet's maximum displacement rises to 2.252 mm, which, while more than double the previous value, remains minimal compared to the P-Sling's displacement of 1218 mm.

Furthermore, stress analysis offers additional insights into the performance of both designs. At a load of 1250 kg, the plastic pallet experiences a maximum stress of 1.342e+07 N/m², whereas the P-Sling design undergoes a much higher maximum stress of 6.690e+07 N/m². When the load is increased to 2000 kg, the plastic pallet's maximum stress rises to 2.112e+07 N/m², while the P-Sling's stress increases to 1.037e+08 N/m². This significant difference underscores the plastic pallet's superior ability to handle increased loads compared to the P-Sling design.

The statement "*Displacement Simulation Comparison with 2000-kg Load*" suggests that there is a comparison being made between two designs, likely the P-Sling and conventional plastic pallet, under the specific condition of a 2000-kg load. This comparison aims to evaluate how each design performs in terms of displacement when subjected to this load.

"Stress analysis" offers additional insights into the performance of both designs indicates that beyond displacement, the study also examines how each design handles stress under the same load conditions. Stress analysis provides important information about structural strength, potential failure points, and overall durability of the designs.

Together, these statements highlight a comprehensive evaluation using Finite Element Analysis (FEA) to understand how the P-Sling and plastic pallet designs perform under heavy loads, focusing on both displacement and stress to provide a thorough assessment of their respective capabilities. This approach helps in identifying strengths, weaknesses, and areas for potential improvement in each design.

Table 4. Displacement simulation comparison with 1250-kg load.

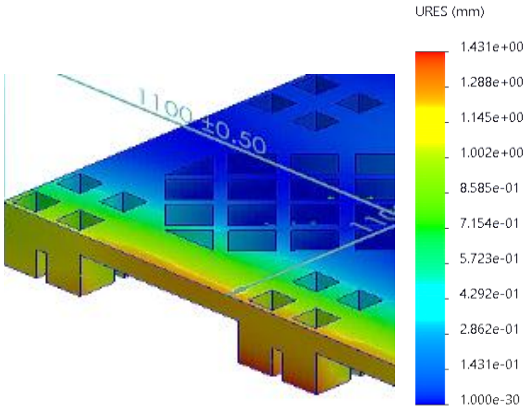
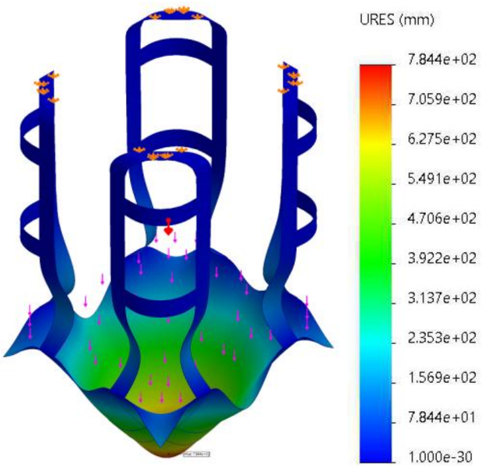
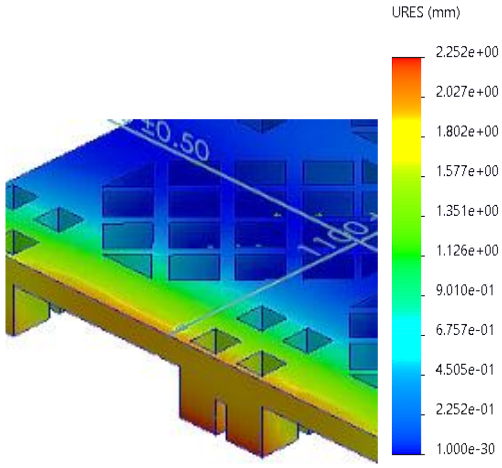
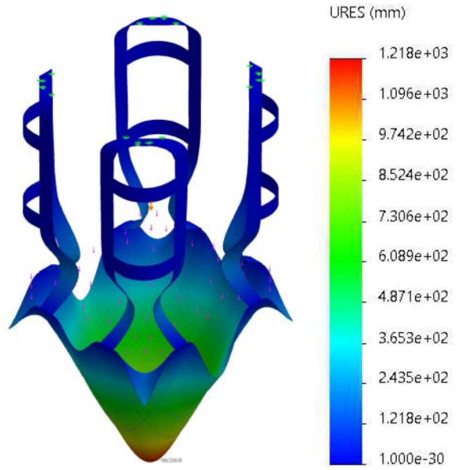
<table>
<tr><th colspan="2">1250-kg Load</th></tr>
<tr><td>Max URES</td><td>Material: HDPE Plastic Pallet</td></tr>
<tr><td>1.431e+00 mm</td><td>
</td></tr>
<tr><td></td><td>Material: Suggested P-Sling Design</td></tr>
<tr><td>7.844e+02 mm</td><td>
</td></tr>
</table>

Table 5. Displacement simulation comparison with 2000-kg load.

<table>
<tr><th colspan="2">2000-kg Load</th></tr>
<tr><td>Max URES</td><td>Material: HDPE Plastic Pallet</td></tr>
<tr><td>2.252e+00 mm</td><td>
</td></tr>
<tr><td></td><td>Material: Suggested P-Sling Design</td></tr>
<tr><td>1.218e+03 mm</td><td>
</td></tr>
</table>

For *Stress Simulation Comparison with 1250-kg Load*, it suggests that there is a comparison being conducted between two designs, likely the P-Sling and conventional plastic pallet, under the specific condition of a 1250-kg load. This comparison aims to evaluate how each design performs in terms of stress distribution and resilience when subjected to this load.

This analysis provides insights into how well each design can handle the applied load without exceeding stress limits that could lead to structural failure or deformation. It allows for a detailed examination of the stress patterns and concentrations within each design, highlighting areas of potential weakness or strength under such loading conditions. Simply saying that this indicates a focused study using Finite Element Analysis (FEA) to assess and compare the stress responses of different designs, contributing to a deeper understanding of their performance characteristics in practical applications.

However, while applying FEA for simulating the force distribution around the P-Sling structure is effective and provides valuable insights into potential failure points for maintenance purposes, other related factors such as material fatigue, impact resistance, and environmental conditions should also be considered.

Addressing these factors is important for ensuring the long-term strength and reliability of the P-Sling, as well as the safety of both the materials it carries and the people handling it. Solving these issues will not only enhance the P-Sling's performance but also contribute to overall operational efficiency and safety.

Table 6. Stress simulation comparison with 1250-kg load.

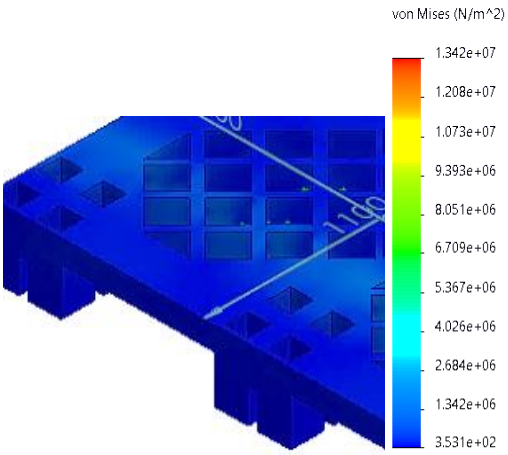
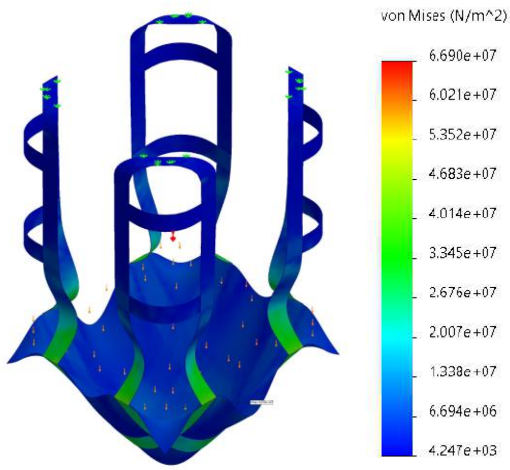
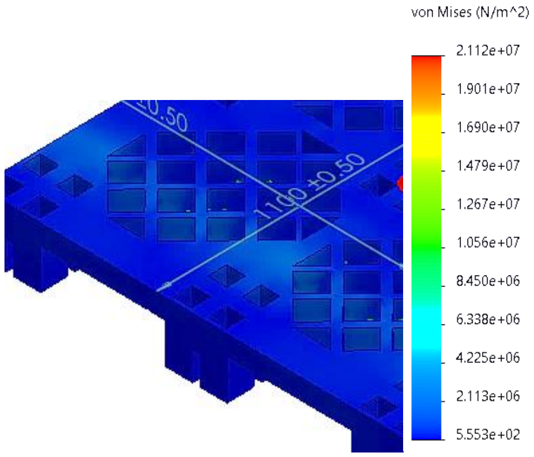
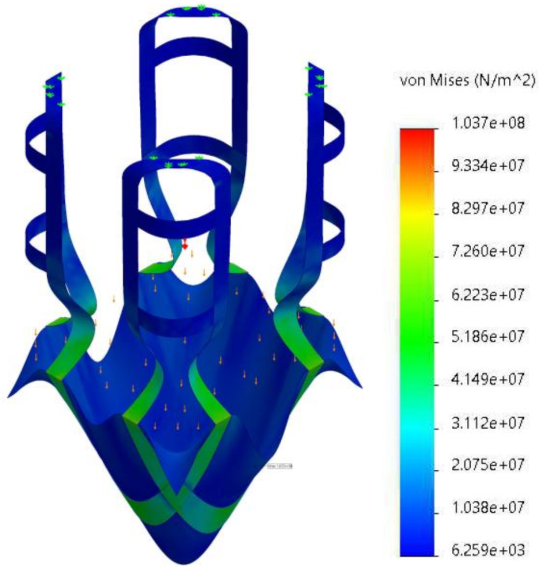
1250-kg Load	
Max von Mises (N/m^2)	**Material:** HDPE Plastic Pallet
1.342e+07	
	Material: Suggested P-Sling Design
6.690e+07	

Table 7. Stress simulation comparison with 2000-kg load.

2000-kg Load	
Max von Mises (N/m^2)	**Material:** HDPE Plastic Pallet
2.112e+07	
	Material: Suggested P-Sling Design
1.037e+08	

4.3. Product Design and Development on "P-Sling" Design

Fault Tree Analysis (FTA) is a systematic, deductive method used to identify potential causes of system failures [15]. By constructing a logical diagram that maps out the pathways to failure, FTA helps in understanding how various factors contribute to potential breakdowns. This analysis is particularly valuable in complex systems, such as the P-Sling material handling platform, where multiple elements must work together seamlessly to ensure reliability and performance.

The diagram of the fault tree analysis is shown in Fig. 6. From the figure, it is shown that three main events could cause failure while using the P-Slings: *poor assembly, large load size,* and *overweight load.* If any of these events happen,

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the P-Sling will fail. For poor assembly, two primary issues can independently cause failure: weak stitches at the connection points and incorrect assembly.

In the case of a large load size, the base area may not be able to support the entire load, leading to failure. Additionally, if the load is too large, the side belts and adjustable belt may not secure the load adequately, resulting in failure. Lastly, an overweight load can cause failure as the side belt, rubber handle, and base may not withstand the excessive force, leading to a breakdown.

Further, environmental factors such as extreme temperatures, exposure to chemicals, or UV radiation can exacerbate these failure modes. These external conditions can weaken the materials over time, reducing the P-Sling's load-bearing capacity and increasing the likelihood of failure. By understanding these potential failure points, FTA provides a clear framework for improving the design and reliability of P-Slings, ensuring they can handle various load scenarios more effectively. Implementing preventive measures such as reinforced stitching, proper training for assembly, and material enhancements can significantly mitigate these risks, resulting in a more robust and dependable material handling solution.

4.4. Discussion

Plastic pallets are designed to be strong and rigid, ensuring they can handle significant loads with minimal deformation. This rigidity allows them to maintain their structural integrity and perform reliably under heavy loads, making them a popular choice in various industries. In contrast, P-Slings are designed with flexibility in mind, which can lead to higher displacement under load. This inherent flexibility is a double-edged sword, while it may offer certain advantages in terms of adaptability and ease of handling, it also means that the P-Sling may deform more significantly when subjected to the same load. The simulations clearly demonstrated that plastic pallets could handle the load firmly, with only minor deformations observed. Specifically, the simulations showed a slight bend on the sides of the plastic pallets. While this bending is relatively minor, it raises concerns about the long-term durability of the pallets. Prolonged use under constant load may exacerbate this bending, potentially leading to a breakdown or failure over time. This aspect of plastic pallet performance warrants further investigation to ensure their reliability in prolonged usage scenarios.

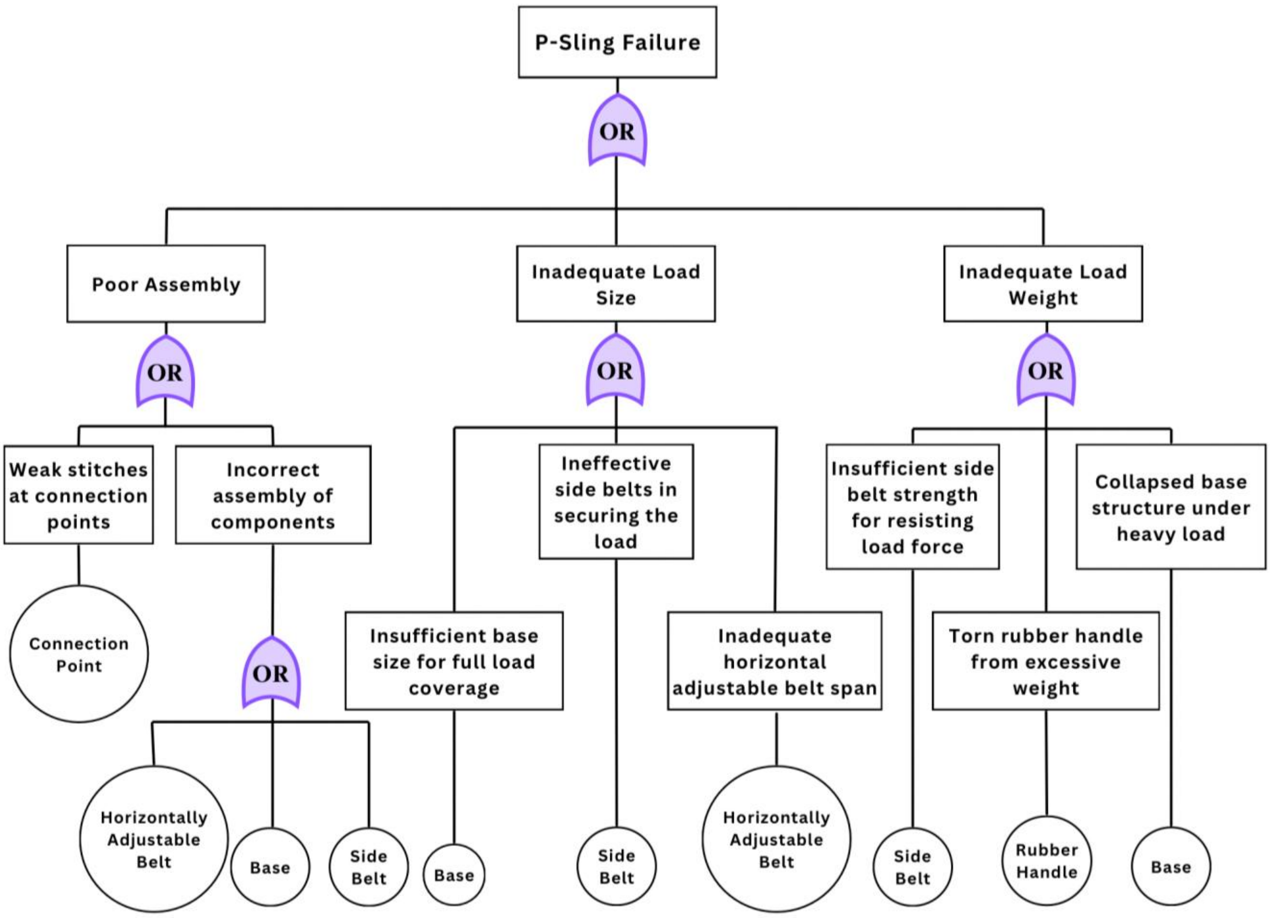


Fig. 6. Fault tree analysis.

On the other hand, the simulations of the P-Sling revealed very high displacement and stress levels. These findings are critical because they indicate that the current design of the P-Sling may not be suitable for practical use under heavy loads. The displacement and stress values were so high that they suggest the P-Sling could experience significant deformation and possibly fail when used in real-world applications. This is a major concern for the viability of the P-Sling design as it currently stands. Additionally, Fault Tree Analysis (FTA) is a widely used technique for failure analysis, simplifying complex system failures into a single diagram. By systematically placing all possible causes of failure on a chart in sequence and connecting them through "AND/OR" gates, FTA identifies the relationships and dependencies between different failure events. This top-down approach, as shown in Fig. 6, reveals that the primary causes of P-Sling failures are poor assembly, large load size, and overweight load. Each of these events can independently lead to failure: poor assembly due to weak stitches or incorrect assembly, large load size overwhelming the base area and belts, and overweight load exceeding the strength of the side belts, rubber handle, and base. Understanding these failure points allows decision-makers to take preventive actions, improving the design and reliability of P-Slings to handle various load scenarios more effectively.

4.5. Suggestion for Improvement

To address the issues identified in the simulations, it is suggested to increase the thickness of the P-Sling's base from 1 mm to 10 mm. This proposed modification aims to reduce the displacement observed in the model, thereby enhancing its structural integrity and load-handling performance. By increasing the thickness, the P-Sling would likely become more rigid and better able to distribute the load, reducing the overall stress and displacement. This change could make the P-Sling a more viable alternative to traditional plastic pallets, provided the modification results in improved performance without compromising other desirable features of the design.

The new finite element analysis is conducted after the increase of the base thickness of the model to 10 mm. The result is shown in Table 8 and 9. From the result, it is shown that when the load is at 1250 kg the displacement in the displacement plot has been decreased significantly to 17.36 mm, which is a relatively small displacement for such a device. Additionally, the stress plot shows that the stress has decreased to 3.417e+07 N/m², which is much smaller than before. When the load is increased to 2000 kg, the P-Sling seems to behave much better with lower stress and displacement values, the result shows the maximum displacement of 2.418e+01 mm and maximum stress of 4.664e+07 N/m².

The findings from this study suggest that applying the proposed improvements could help enhance the performance of the P-Sling model in future research. Key areas for further design development include improving load capacity and durability. After refining the design through several rounds of updates, creating a physical prototype would be the next logical step.

This prototype should be tested under controlled conditions to evaluate its performance. A step-by-step approach like this allows for continuous improvement and helps confirm the P-Sling's potential as a flexible and reliable alternative to traditional plastic pallets in industrial settings.

Table 8. Simulation of improved model with 1250-kg load.

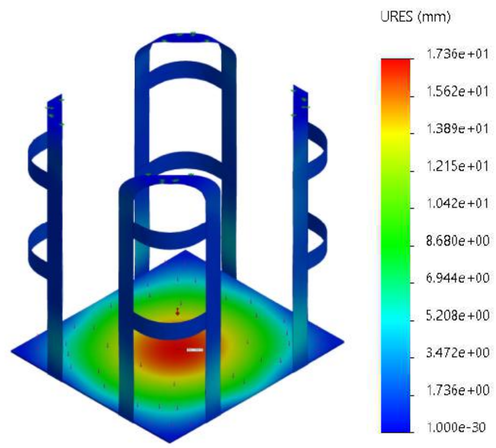
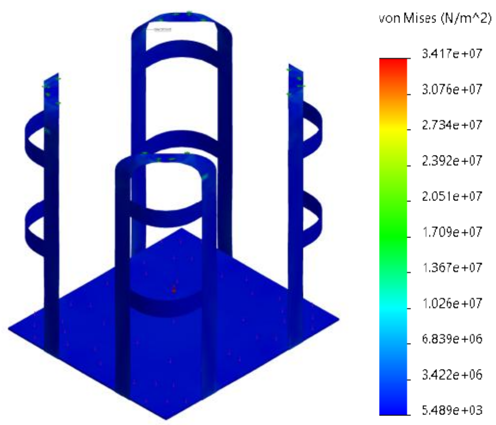
	1250-kg Load
Max Value	**Material:** Suggested P-Sling Design
Displacement Plot 1.736e+01 mm	
Stress Plot 3.417e+07 N/m²	

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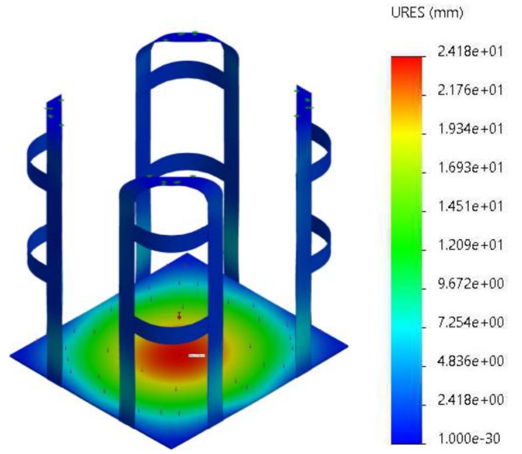
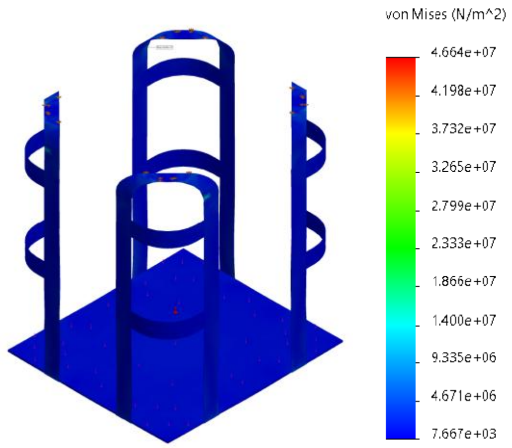
Table 9. Simulation of improved model with 2000-kg load.

	2000-kg Load
Max Value	**Material: Material:** Suggested P-Sling Design
Displacement Plot 2.418e+01 mm	
Stress Plot 4.664e+07 N/m^2	

Simulation results show that the improved design performs better in both stress and displacement. The displacement values remain within acceptable and safe limits, and the reduced stress levels improve the design's overall reliability.

However, while the new design shows improvement, the plastic pallet still performs better in terms of lower stress and displacement. This is expected, as the P-Sling is designed to be flexible, unlike the plastic pallet, which is built for rigidity and strength.

To ensure the success of the P-Sling, other factors such as cost and material selection must also be considered. Choosing suitable materials can help balance performance with affordability, making the design more competitive. These factors open opportunities for further development to meet both technical and economic requirements for real-world use.

4.6. Problems and Difficulties

During the simulation of the plastic pallet, a small adjustment to the deformation scale was necessary to obtain accurate results. The default automatic setting made the deformation look larger than it actually was, leading to misleading visuals, as shown in Fig. 7. To correct this, the deformation scale was changed to true scale, which provided a more realistic view of the model. This adjustment ensured consistency with the expected results shown in Tables 4, 5, 6, and 7.

The P-Sling style presents several advantages over conventional pallets, including efficient space utilization, lighter weight for cost-effective transport, customization to accommodate various product shapes and sizes, enhanced durability for prolonged use, improved ergonomics for easier handling, and a reduced environmental footprint through the use of sustainable materials and reusability.

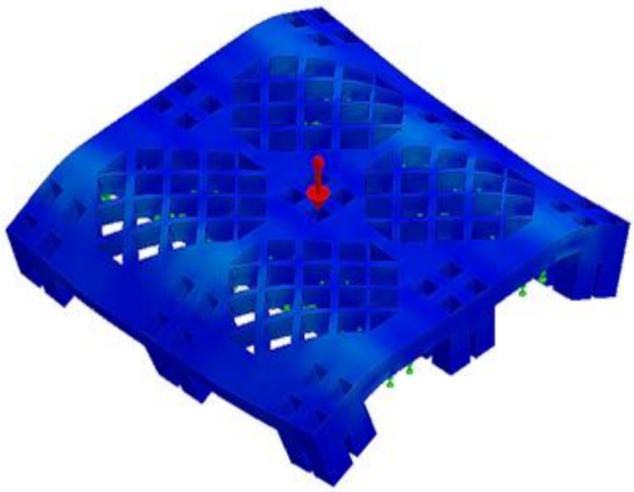


Fig. 7. Inaccurate simulation stress plot of plastic pallet.

5. Conclusion

The finite element analysis conducted on both the conventional plastic pallet and the proposed P-Sling design provided a detailed comparison of their load-handling capabilities. After the simulation, the plastic pallet exhibited minor bending and deformation, which could lead to potential failure with prolonged use, despite its design to be strong and rigid. In contrast, the initial P-Sling design showed significantly higher displacement and stress, indicating that it may not sustain heavy loads effectively.

To address this issue, it is suggested to increase the base thickness of the P-Sling from 1 mm to 10 mm. After the simulation with the base thickness of 10 mm, the result from the modification significantly reduced the displacement and stress, improving its load-handling performance. Despite this improvement, the plastic pallet still demonstrated lower overall stress and displacement, maintaining its superior structural integrity. However, the

P-Sling's design philosophy is centered around flexibility, allowing it to deform under load without causing long-term damage. This characteristic can be beneficial in applications requiring adaptability and resilience to shape changes.

The study's scope and limitations focus on the sizes, weights, and particle sizes of tapioca pearls within the range of 1 to 2.5 mm. These pearls are exclusively produced from tapioca starch and undergo processes limited to granulation, roasting, and drying. The weight is standardized with 1000 particles equaling 0.929 g, providing insights into the density and volume of each particle. The study considers the capacities for filling sago bags, ranging from 15 kg to 30 kg.

In conclusion, while the plastic pallet remains a robust and reliable option, the improved P-Sling design offers a promising alternative with its enhanced performance and inherent flexibility, suitable for dynamic load environments. Further research and optimization could make the P-Sling a strong competitor to traditional plastic pallets.

6. Contributions

6.1. Finite Element Analysis (FEA)

The existing body of literature extensively explores the transformative utilization of factory waste to create innovative products, as evidenced by numerous articles available on the internet. However, a thorough investigation reveals that none of these studies have specifically examined the potential of repurposing defective tapioca pearls. This research gap highlights a unique and unexplored opportunity to contribute to the field by examining the viability and novel applications of defective tapioca pearls, setting this research apart from the existing body of knowledge.

Finite Element Analysis (FEA) is utilized in this study to predict deformation patterns and identify potential structural issues within the design. FEA helps in understanding the force distribution around the area of interest, allowing design engineers to anticipate unexpected situations during real-time use. By simulating these conditions, FEA ensures the safety and reliability of the design, enabling improvements before actual production. This methodology not only validates the design but also optimizes material properties, contributing to the overall quality and performance of the product.

6.2. Logistics and Supply Chain Management

Recent advances in logistics and supply chain management have focused on developing practical and effective solutions to address real-world challenges faced by businesses [24-27]. For instance, a delivery service management system using Google Maps technology has been created to improve route planning and operational efficiency, especially for small and medium enterprises in emerging countries [29]. Building on this, sustainable multi-objective production and distribution planning models have been introduced to balance the trade-offs between cost, service levels, and environmental impact, thereby promoting greener and more efficient supply chains. Furthermore, a target-oriented approach has been proposed to synchronize production and distribution planning with both sales targets and profit goals, providing strategic decision-making support for complex supply chain operations. In parallel, simulation models have been developed to study the behavior and financial impacts of retail supply chains under uncertainty, focusing on optimizing inventory and distribution decisions. Enhanced optimal inventory control policies for perishable products in retail businesses were examined using comparative simulations under different cost structures to identify the most effective replenishment strategies. Additionally, optimal inventory control policies for hybrid manufacturing–remanufacturing systems were investigated by applying a hybrid simulation–optimization algorithm to balance production and remanufacturing processes, thereby improving overall system profitability. Collectively, these studies contribute significantly to enhancing logistics performance, sustainability, inventory management, and the strategic operation of supply chains in dynamic and complex environments [28-33].

7. Recommendation

This research supports manufacturing processes and competitive industrial strategies, particularly in transportation, mold and die making, storage arrangement, and material handling equipment [34]. It proposes an alternative P-Sling design over traditional pallets for factory use.

Finite Element Analysis (FEA) compares the load-handling capabilities of conventional plastic pallets and the proposed P-Sling design. Initial simulations indicated the need to increase the P-Sling's base thickness for improved load-handling. Enhanced P-Slings showed reduced stress and displacement, while plastic pallets maintained superior structural integrity. The P-Sling's flexibility makes it suitable for dynamic load environments.

The study also examines tapioca pearl characteristics, providing insights into their density and volume. While plastic pallets remain robust, the improved P-Sling design shows promise for adaptable and resilient applications. Further research could make the P-Sling a competitive alternative to traditional pallets. Additionally, the research aims to transform defective tapioca pearls into valuable by-products, moving away from their use as animal feed. This shift increases their value and expands the product offerings of tapioca pearl factories.

To improve the product design and development process and ensure the clarity and quality of the final product, this study applies both Quality Control Circles (QCCs) and Finite Element Analysis (FEA). QCCs, which are groups of employees working together to identify and solve work-related problems, support new product development (NPD) through idea generation, problem-solving, continuous improvement, teamwork, and employee involvement. This research explores how QCCs and FEA can work together to strengthen NPD processes, offering practical insights for organizations looking to improve product quality and competitiveness [27].

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