

Research Article

Design and Development of a Universal Threshing Machine for Commercial Applications

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Abstract

This study reviews existing research on the design, construction, and performance optimization of shredding and threshing machines, with the aim of developing a comprehensive understanding of their operational characteristics and identifying opportunities for improved efficiency. A systematic methodology was adopted, incorporating theoretical machine design, computer-aided modelling, finite element analysis, and motion simulation using Autodesk Inventor and MATLAB. The findings show that the universal shredding and threshing machine performs optimally, achieving an efficiency of approximately 90%, with both shredding and threshing operations executed effectively. Finite element analysis further confirms the structural suitability of the frame and cutting blades, indicating an absence of plastic deformation or failure under operational loads. Motion analysis reveals that the main shaft and tray function proportionally and maintain consistent speeds, with a linear tray velocity of about 48 m/s and an angular shaft speed of approximately 120 rad/s, validating the machine's stable performance characteristics. Based on these outcomes, the study recommends upgrading the electric motor to improve operational efficiency, increasing blade thickness to enhance cutting performance and durability, and incorporating AnyLogic simulation software for more advanced validation of component motion and speed. The insights provided contribute to improved understanding and further optimization of shredding and threshing machine performance for industrial applications.

Keywords

Shredding and Threshing Machine, Finite Element Analysis, Machine Design, Computer-Aided Design

1. Introduction

Threshing is a fundamental postharvest operation that facilitates the separation of edible grain from the protective, non-nutritive chaff that surrounds it. It occurs after harvesting and precedes winnowing, which further segregates loosened chaff from the clean grain (Kumar and Kalita, 2017) [1].

For cereal crops such as rice, millet, sorghum, and maize, threshing constitutes a critical component of the value chain, directly influencing grain quality, processing efficiency, and market value. In many developing countries, including those in sub-Saharan Africa and Southeast Asia, threshing is pre-

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dominantly performed manually, often by hand beating, trampling, or using rudimentary implements. These traditional practices result in high grain loss, reduced throughput, and compromised grain quality due to contamination by dirt, stones, and other foreign materials [2]. Farmers frequently identify threshing as one of the most labor-intensive and time-consuming operations during harvesting [3].

The challenges associated with manual threshing intensify with increasing production demands, as seen in Nigeria's rapidly growing rice sector. The traditional methods, including beating harvested crops on wooden logs or bamboo surfaces, trampling by humans or livestock, or pounding in a mortar and pestle, are associated with low efficiency, broken grains, contamination, and unacceptable postharvest losses [4]. Studies have shown that prolonged manual threshing not only increases fatigue but also leads to grain scattering, qualitative degradation, and microbial contamination, further reducing market value. These inefficiencies underscore the need for mechanized alternatives capable of improving throughput and minimizing drudgery, especially within resource-constrained farming communities. Additionally, research indicates that mechanization significantly enhances postharvest handling by reducing grain damage, lowering foreign-material contamination, and improving drying and storage efficiency [5-7]. Modern threshing machines, whether stand-alone or integrated into combine harvesters, provide higher capacity, improved separation efficiency, and reduced operational labor [8]. Mechanization is also essential for safeguarding product quality in line with increasing global standards for grain purity, shelf stability, and milling yield. According to Wijayanto and Puspitojati [9], optimizing processing conditions through mechanization is critical for achieving higher output and ensuring better grain attributes such as aroma, texture, and extended storage life.

Recent advancements in agricultural engineering have introduced a range of improved threshing technologies targeted at low-income farming communities. These include portable axial-flow threshers, pedal-operated threshers, multi-crop threshers, and integrated shredding-threshing systems [10, 11]. The emerging design trend prioritizes energy efficiency, structural durability, user safety, and adaptability to different grain types and moisture conditions. Finite element analysis (FEA) and computer-aided design (CAD) tools are increasingly utilized to optimize machine components such as blades, shafts, concaves, and frames, ensuring better stress distribution and longer service life [12]. Similarly, simulation environments such as MATLAB, ANSYS, and Autodesk Inventor have enhanced predictive modeling, permitting accurate estimation of power requirements, motion characteristics, impact forces, and material flow during threshing operations [13]. Despite these advances, the adoption of mechanized threshing systems in many developing regions remains limited due to factors such as cost, inadequate training, inconsistent power supply, and poorly developed local manufacturing capacity [14]. Furthermore, existing threshers

often struggle with the rugged and uneven terrain typical of Nigerian farmlands, leading to inefficiencies and operational delays. These shortcomings highlight the need for more robust, locally adaptable, and cost-effective machines that can operate efficiently across various crop types and environmental conditions (covered in this current design). The role of advanced mechanized farming systems remains imperative for optimal farming operations and processing [15].

Given these gaps, this research focuses on the detailed design, development, and performance evaluation of a universal threshing machine intended for commercial applications. The goal is to develop an efficient, durable, and structurally optimized system that reduces labor intensity, enhances grain quality, and increases operational productivity for small- and medium-scale farmers. By integrating modern engineering tools such as CAD modeling, FEA, and dynamic simulation, the study aims to contribute to the growing body of knowledge on innovative postharvest mechanization technologies and provide a practical solution to the challenges of traditional threshing methods.

2. Materials and Method

2.1. Materials

This study employed the following software tools: Autodesk Inventor version 2021 and MATLAB version 2020.

2.1.1. Autodesk Inventor 2021

Autodesk Inventor 2021, a widely recognized computer-aided design (CAD) software, was employed for the geometric modeling and structural integrity assessment of the universal threshing machine. CAD tools play a pivotal role in modern engineering design by enabling the precise creation of solid models and complex assemblies while allowing detailed control over geometric features, material specifications, dimensional constraints, and manufacturing tolerances. In this study, Autodesk Inventor 2021 was used to develop an accurate three-dimensional model of the threshing machine, capturing all functional components and their spatial relationships. The software facilitated detailed visualization of the machine architecture, enabling effective evaluation of component fit, alignment, and assembly feasibility prior to fabrication. In addition, the built-in finite element analysis (FEA) environment was utilized to assess the structural integrity of critical components, particularly the machine frame and cutting blades. These analyses examined stress distributions, deformation behavior, and safety factors under expected operational loads, thereby ensuring that the components could withstand service conditions without structural failure. The use of Autodesk Inventor, therefore, contributed significantly to design validation, risk reduction, and optimization of the machine before physical production.

2.1.2. MATLAB 2020

MATLAB 2020, integrated with the Simscape tool, was employed to analyze and simulate the dynamic behavior of the universal threshing machine. MATLAB provides a robust computational environment for numerical analysis, modeling, and simulation, while Simscape extends its capabilities by enabling the physical modeling of mechanical systems using energy-based components. In this work, Simscape was applied to model the kinematic and dynamic interactions of the machine's main shaft and tray assembly. The simulation enabled evaluation of motion characteristics such as angular velocity, linear velocity, and synchronization between moving components under operating conditions. This approach was essential for verifying the functional performance of the machine, ensuring smooth power transmission, and confirming that the motion of the shaft and tray remained proportional and stable throughout operation. The use of MATLAB and Simscape provided valuable insights into system behavior that could not be easily obtained through static analysis alone. By allowing virtual testing under different operating scenarios, the simulation framework supported performance optimization, reduced the likelihood of mechanical inefficiencies, and enhanced the reliability of the final design. Overall, the integration of MATLAB-based dynamic simulation complemented the CAD-based structural analysis, resulting in a comprehensive evaluation of both the mechanical strength and operational performance of the threshing machine.

2.1.3. Description of the System Components

Hopper

The hopper serves as the primary feed inlet through which millet panicles are introduced into the threshing drum. For enhanced durability, corrosion resistance, and cost efficiency, the hopper is recommended to be fabricated from galvanized steel. The use of galvanized material minimizes rust formation and extends the service life of the component, particularly under humid operating conditions.

Threshing Chamber

The threshing chamber constitutes the core unit where the separation of millet grains from the straw is achieved. It is fabricated from mild steel and comprises a rotating threshing drum fitted with beater pegs and a stationary concave grid. The combined action of impact and rubbing between the rotating pegs and the concave bars facilitates effective detachment of grains from the panicles.

Separating Chamber

The separating chamber performs the final cleaning operation by separating the threshed grains from foreign materials such as chaff, sand, and broken grains. Constructed from mild steel, the chamber incorporates two reciprocating sieves and a centrifugal fan. The sieves enable size-based separation, while the fan supplies an air stream that prevents the accumulation of lighter impurities on the sieve surfaces, thereby improving separation efficiency.

Blower Housing

The blower housing was fabricated from mild steel and encloses the blower blade and shaft assembly. It provides structural support and ensures proper alignment and safe operation of the air delivery system used during the cleaning process.

Threshing Drum

The threshing drum is housed within the threshing chamber and is manufactured from galvanized steel to enhance resistance to wear and corrosion. The drum is mounted on a shaft positioned above the concave with a clearance of approximately 6 mm, which is critical for achieving effective grain separation without excessive grain damage.

Screen

The screen is a concave, perforated component fabricated from mild steel. It plays a vital role in the separation process by allowing threshed grains to pass through the perforations while retaining larger unwanted materials such as straw and unthreshed panicles.

2.1.4. Operational Principle of the Machine

The threshing drum shaft is driven by an electric motor, while power transmission to the cleaning chamber shaft is achieved through a belt and pulley system. The shafts are supported by bearings to ensure smooth and stable rotational motion. Millet panicles introduced into the machine through the hopper are conveyed into the threshing chamber, where grain separation occurs. Within the threshing chamber, a rotating cylinder fitted with beater pegs operates over a stationary concave grid. As the panicles pass between the rotating pegs and the concave bars, grains are detached through repeated impact and shearing actions. The majority of the separated grains pass through the concave grid and are directed into the cleaning unit. The cleaning unit consists of two oscillating sieves and a centrifugal fan that forces air through the sieves. The upper sieve retains chaff and larger impurities while allowing grains to pass through, whereas the lower sieve, referred to as the grain sieve, contains perforations sized to match the grain diameter. This sieve further separates grains from sand, debris, and broken particles. The airflow generated by the blower prevents lighter materials from settling on the sieves, thereby enhancing cleaning efficiency. Clean grains are collected via grain pans located beneath the grain sieve and discharged through the clean grain outlet. Simultaneously, broken grains and smaller unwanted particles are conveyed to a separate outlet, ensuring effective segregation and high-quality grain recovery.

2.2. Method

This section presents the methodological framework adopted for the development of the universal threshing machine. The methodology comprises three interrelated stages: machine design, structural integrity analysis, and motion simulation of the shaft and tray assemblies. These stages

collectively ensure that the developed machine meets the required functional, mechanical, and operational performance criteria. The systematic integration of design, analysis, and simulation provides a robust basis for achieving efficiency, durability, and reliability in practical applications.

2.2.1. Machine Design

The design of the universal threshing machine was carried out with the objective of achieving effective shredding and threshing of a wide range of crops. Emphasis was placed on functional versatility, structural robustness, and ease of operation. A key design consideration was the estimation of the total load of foam or crop material, fixed at 60 kg. This parameter served as a critical input in determining component dimensions, material selection, and overall structural configuration, ensuring the machine's ability to accommodate varying operational loads. The machine is powered by a 1.5 HP electric motor operating at a rotational speed of 1400 rpm. This power rating was selected to provide sufficient torque and rotational energy for consistent shredding and threshing operations without excessive energy consumption. The design incorporates a coordinated assembly of components, including a rigid supporting frame, a rotating shaft, a tray mechanism, and a cutting blade system. Each component was dimensioned and configured to function synergistically, enabling smooth material flow, effective crop separation, and stable operation. The overall design prioritizes mechanical simplicity, operational efficiency, and adaptability to different agricultural contexts. Table 1 presents a summary of the critical design parameters of the universal threshing machine. Also, the CAD models of the universal threshing machine are presented in Figures 1-4.

Table 1. Summary of the critical component design values of the machine.

S/N	Components	Specification
1	Electric motor	1.5HP
2	Drum peripheral speed, V	2300m/s
3	Drum diameter, D_p	230mm
4	Revolutional speed of the pulley, N	1150rpm
5	Total mass of drum, M_d	10kg
6	Radius of the driven pulley, R	75mm
7	Effective radius of the drum, r	115mm
8	Nominal pitch length of belt, L	2295.6mm
9	Efficiency of the machine	90%
10	Centre distance between the two pulleys, c	920mm
11	Diameter of the driver pulley, d	140mm

S/N	Components	Specification
12	Diameter of drum shaft pulley, D	150mm

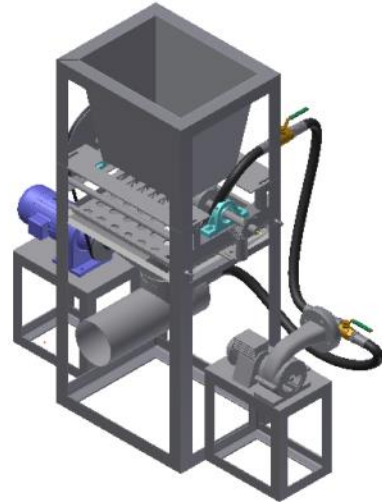


Figure 1. 3D CAD model of the shredding and threshing machine.

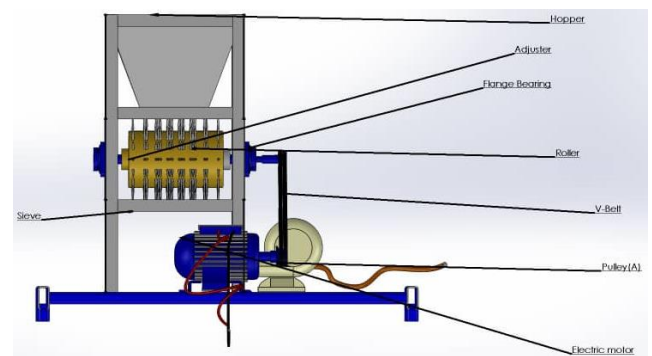


Figure 2. 3D left end view of the machine.

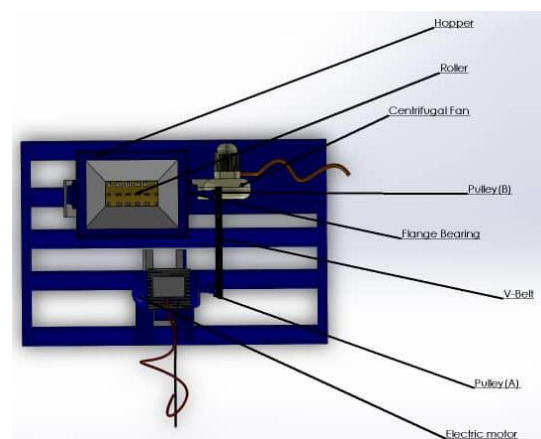


Figure 3. 3D top view of the machine.

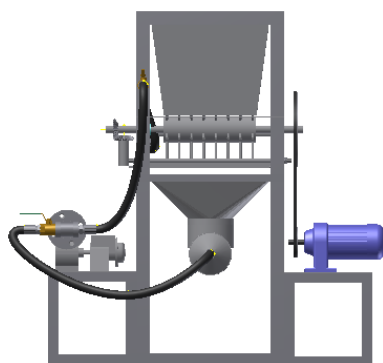


Figure 4. 3D right end view of the machine.

2.2.2. Structural Integrity Analysis (SIA)

Structural integrity analysis was conducted to evaluate the ability of the universal threshing machine to withstand operational stresses and mechanical loads during service. This analysis was essential to ensure safe operation, prevent premature failure, and enhance service life. Particular attention was given to critical components such as the frame and cutting blades, which are subjected to repeated loading, impact forces, and torsional stresses. Advanced finite element analysis (FEA) techniques were employed using Autodesk Inventor 2021 to simulate real-world loading conditions. The analysis assessed stress distribution, deformation behavior, and potential failure regions within the machine components. Material properties and boundary conditions were defined in accordance with standard engineering practice.

(i). SIA of the Frame

To evaluate the structural stability of the machine frame, a detailed frame analysis was conducted. Fixed boundary constraints were first applied to anchor the base of the frame to the reference plane (ground), ensuring a realistic simulation of operational conditions. Subsequently, the total weight of the machine components was determined and appropriately distributed across the load-bearing members of the frame. The combined mass of all machine components was calculated to be 68 kg, comprising 40 kg attributed to the upper section and 28 kg to the lower section of the structure. Based on the transverse perimeter length of the machine, measured as 1800 mm, equivalent uniformly distributed loads were computed and applied to the respective sections. The resulting distributed loads were 0.218 N/mm for the upper section and 0.1526 N/mm for the lower section. The applied loading conditions enabled accurate assessment of stress distribution and deformation characteristics under service loads. Figure 5 illustrates the frame structure under the applied loading conditions, highlighting the load application and constraint configuration used in the analysis. In addition, Table 2 shows the material properties of the machine frame component.

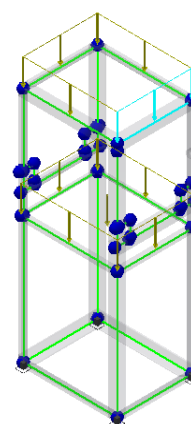


Figure 5. The loaded frame member (continuously distributed loads and fixed base).

Table 2. The material properties of the machine frame.

Name	Steel, Mild	
General	Mass Density	7.860 g/cm ³
	Yield Strength	207.000 MPa
	Ultimate Tensile Strength	345.000 MPa
Stress	Young's Modulus	220.000 GPa
	Poisson's Ratio	0.275 ul
	Expansion Coefficient	0.0000120 ul/c
Stress Thermal	Thermal Conductivity	56.000 W/(m K)
	Specific Heat	0.460 J/(kg K)

(ii). SIA of the Machine Blades

The structural strength of the threshing blades was also assessed to ensure their ability to withstand operational loads without failure. In this analysis, the two mounting slots and the transverse section at the rear end of the blade were constrained to simulate rigid attachment during operation. A pressure load of 0.0199 N/mm² was applied to the blade surface. This value was derived from an assumed uniformly distributed load corresponding to a total mass of 60 kg acting over a blade sectional area of 49,545.238 mm². The applied load represents the combined effects of crop resistance and dynamic forces encountered during the threshing process. The material properties of the blade are presented in Table 3. Figure 6 delineates the blade model under the applied loading and boundary conditions.

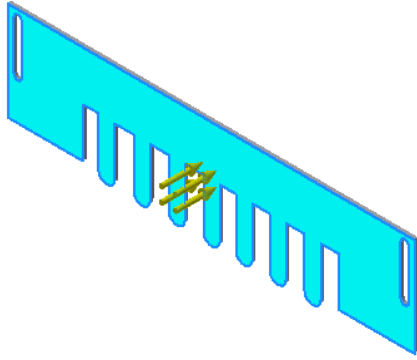


Figure 6. Loaded threshing blade.

Table 3. Material properties of the threshing blades.

Name	Steel	
General	Mass Density	7.85 g/cm ³
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
	Young's Modulus	210 GPa
Stress	Poisson's Ratio	0.3 ul
	Shear Modulus	80.7692 GPa
	Expansion Coefficient	0.000012 ul/c
Stress Thermal	Thermal Conductivity	56 W/(m K)

Name	Steel
Specific Heat	460 J/(kg c)

2.2.3. Motion Simulation: Optimizing Performance Dynamics

Motion simulation was carried out to evaluate and optimize the dynamic behavior of the machine's shaft and tray components during operation. MATLAB 2020, integrated with the Simscape toolbox, was utilized to model the kinematic and dynamic interactions within the system. The simulation framework enabled the analysis of rotational speed, angular displacement, linear velocity, and synchronization between moving components. The simulation results provided insights into the operational stability and efficiency of the machine under simulated working conditions. The shaft and tray motions were observed to be proportional and stable, indicating effective power transmission and balanced mechanical interaction. Potential inefficiencies and undesirable dynamic responses were identified and addressed at the simulation stage, thereby reducing the likelihood of performance issues during physical operation. The motion simulation process played a crucial role in refining the design, enhancing energy efficiency, and ensuring optimal performance of the universal threshing machine in practical agricultural and industrial applications. Figure 7 delineates the force analysis used in simulating the two-component motions.

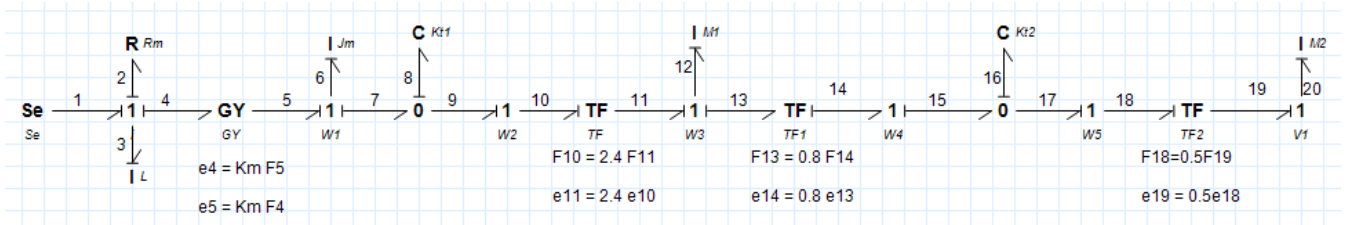


Figure 7. Force-motion analysis.

The modelling of the universal shredding and threshing machine's performance was based on the following assumptions.

Power losses due to mechanical errors in pulleys, belts, bearings, gears, crank mechanism components, and tray slides were neglected.

The velocity of the components of the crank mechanism was neglected; hence, the mechanism was assumed a transformer.

The electric motor has winding resistance, R_m , inductance L , motor constant K_m , and rotor inertia J_m .

The shaft mass for the motor was neglected.

Torsional stiffness of the motor shaft and other shafts was represented with K_m .

Masses of pulleys and gears were neglected.

Stiffness of the main shaft was assumed to be unity, which implied that the shaft is rigid.

Based on these assumptions, the simulation models delineated in Figure 7 were derived thus.

$$\dot{P}_3 = e_3 \quad (1)$$

$$e_3 = e(t) - e_2 - e_4 \quad (2)$$

$$e_2 = R_2 F_2 = R_m F_2 \quad (3)$$

$$F_2 = F_3 = \frac{P_3}{L} \quad (4)$$

$$e_4 = K_m F_5 \quad (5)$$

$$F_5 = F_6 = \frac{P_6}{J_m} \quad (6)$$

Therefore,

$$\dot{P}_3 = e(t) - R_m \frac{P_3}{L} - K_m \frac{P_6}{J_m} \quad (7)$$

Furthermore,

$$\dot{P}_6 = e_6 \quad (8)$$

$$e_6 = e_5 - e_7 \quad (9)$$

$$e_5 = K_m F_4 \quad (10)$$

$$F_4 = F_3 = \frac{P_3}{L} \quad (11)$$

$$e_7 = e_8 = \frac{q_8}{K_{t1}} \quad (12)$$

Therefore,

$$\dot{P}_6 = K_m \frac{P_3}{L} - \frac{q_8}{K_{t1}} \quad (13)$$

In addition,

$$\dot{P}_6 = F_8 \quad (14)$$

$$F_8 = F_7 - F_9 \quad (15)$$

$$F_7 = F_6 = \frac{P_6}{J_m} \quad (16)$$

$$F_9 = F_{10} = 2.4 F_{11} \quad (17)$$

$$F_{11} = F_{12} = \frac{P_{12}}{m_1} \quad (18)$$

Therefore,

$$\dot{q}_8 = \frac{P_6}{J_m} - 2.4 \frac{P_{12}}{m_1} \quad (19)$$

Solving further for P_{12} model,

$$\dot{P}_{12} = e_{12} \quad (20)$$

$$e_{12} = e_{11} - e_{13} \quad (21)$$

$$e_{11} = 2.4 e_{10} \quad (22)$$

$$e_{10} = e_9 \quad (23)$$

$$e_9 = e_8 \quad (24)$$

$$e_8 = \frac{q_8}{K_{t1}} \quad (25)$$

$$e_{13} = \frac{e_{14}}{0.8} \quad (26)$$

$$e_{14} = e_{15} = e_{16} = \frac{q_{16}}{K_{t2}} \quad (27)$$

Therefore,

$$\dot{P}_{12} = 2.4 \frac{q_8}{K_{t1}} - \frac{1}{0.8} \frac{q_{16}}{K_{t2}} \quad (28)$$

The universal shredding/threshing machine was constructed using the computed design variables. The machine was tested, and its efficiency was computed.

3. Results and Discussions

3.1. The Result of Structural Integrity Analysis for the Machine's Frame

The displacement behaviour of the machine frame when impacted by a continuously distributed load is shown in Figure 8.

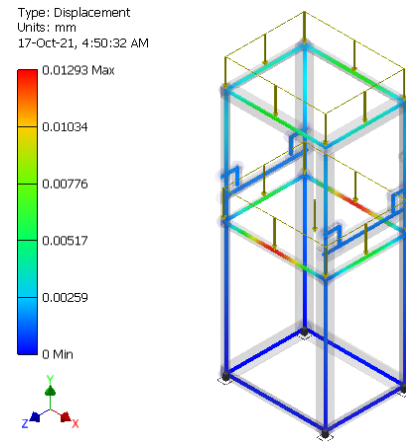


Figure 8. Displacement of the machine frame under distributed loads.

The structural response of the frame under the applied loads revealed a maximum displacement of 0.01293 mm, occurring at the lower section of the frame, which supports the threshing shaft and blade assembly during operation (Figure 8). This displacement is attributed to the dynamic influence of the rotating shaft and blade assembly during shredding and threshing processes. The magnitude of the observed displacement remains significantly below the elastic limit of the frame material, indicating that no plastic deformation is induced. Consequently, the frame maintains structural integrity under operational conditions. Other regions of the frame exhibited negligible deformation, all of which remained within permissible strain limits, further confirming the adequacy of the selected material and design.

The reaction forces generated at the fixed supports were evaluated and are presented in Figures 9 and 10. As shown in Figure 9, the maximum reaction force components were 60.02 N in the x-direction, 47.12 N in the y-direction, and 227.4 N in the z-direction. These reaction forces indicate that the frame effectively resists the applied distributed loads. Notably, the reaction force in the y-direction, which corresponds to the primary loading direction, further confirms the suitability of the frame material and geometry for the intended application.

The corresponding reaction moments are illustrated in Figure 10. The maximum bending moments recorded were 3147 N mm, 3940 N mm, and 10.96 N mm in the x-, y-, and z-directions, respectively. The highest moments in the x- and

y-directions were observed at the upper section of the frame, while the maximum moment in the z-direction occurred at the lower section. These moment values are well within the allowable limits of the frame material, demonstrating sufficient resistance to bending and torsional effects induced by operational loads.

The shear stress distribution within the frame material is presented in Figure 11. The stress contours indicate uniform stress transfer across the structural members, with no localized stress concentrations exceeding the material's yield strength. This further confirms that the frame design is structurally sound and capable of safe operation throughout its service life.

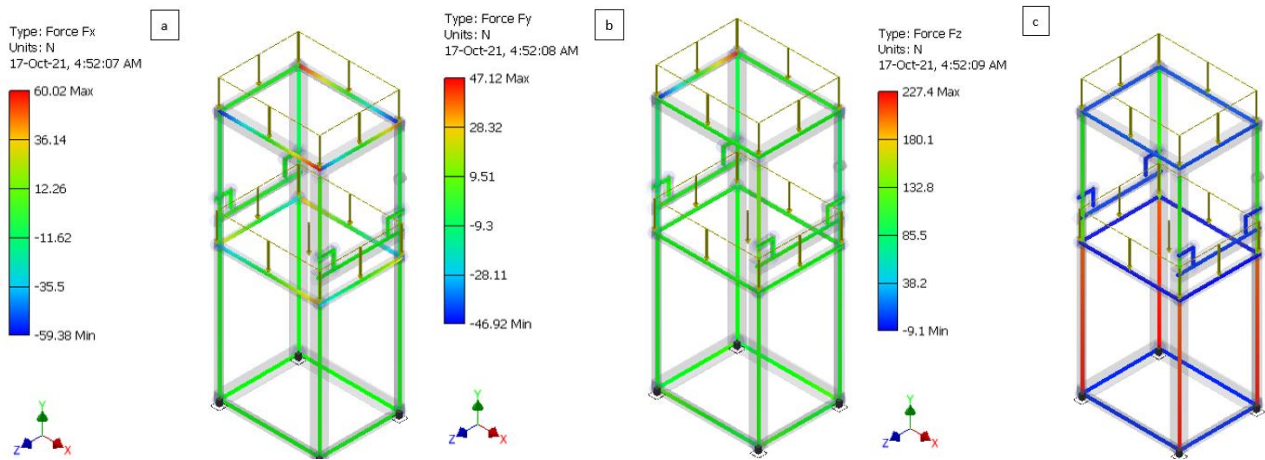


Figure 9. Reactions forces acting on the frame in the (a) x-direction, (b) y-direction, and (c) z-direction.

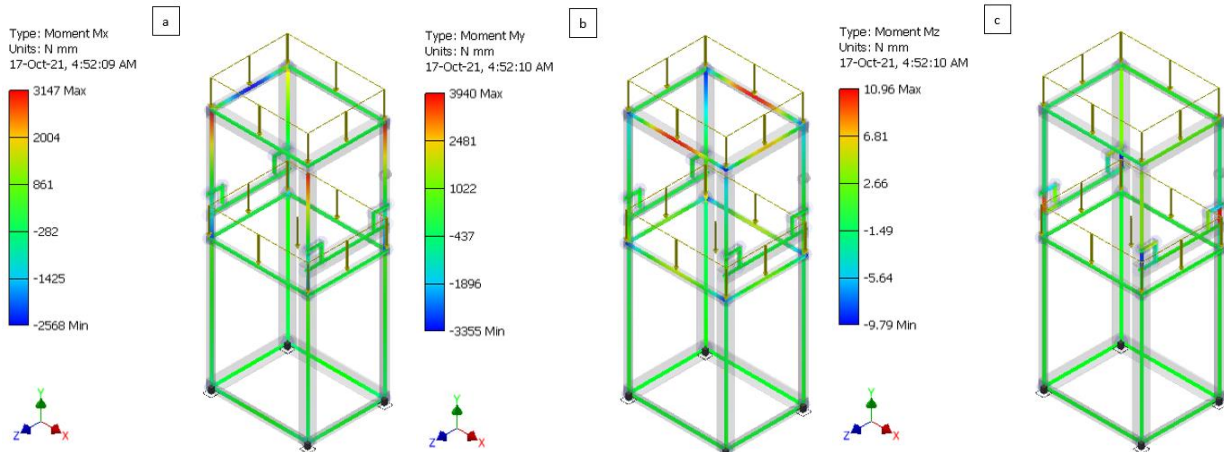


Figure 10. Force moments in the (a) x-direction, (b) y-direction (c) z-direction.

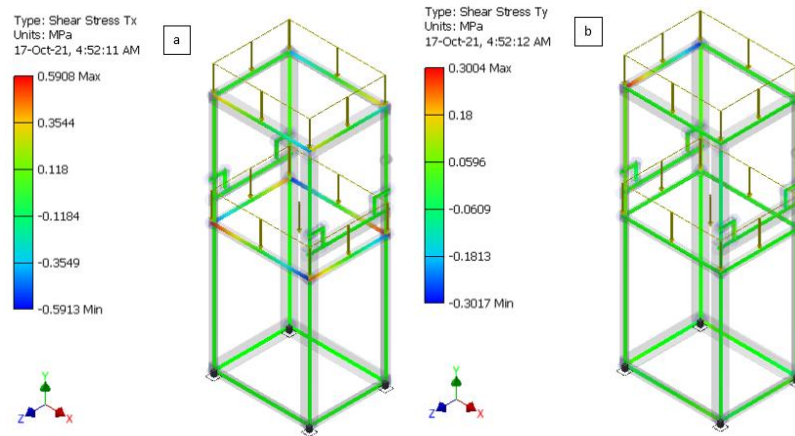


Figure 11. Shear stress distribution on the frame in the (a) x-direction and (b) y-direction.

From Figure 11, the frame material is very safe for machine construction as the maximum shear stress observed at the upper section of the frame (Figure 11b) in the y-direction had a maximum value of 0.3004MPa which is very small compared to the yield and ultimate strength of the frame material-207MPa and 345MPa respectively. This implies that the frame will not experience plastic deformation while in idle or service mode. See Appendix A3 for the summary of the deformation and stress behaviours of the frame structure.

3.2. Result of the Structural Integrity Analysis of the Blade

To ascertain the structural strength of the material used in the threshing blade construction, its structural strength quality was analyzed, and the result of the stress distribution on the blade material under an impressed load is presented in Figure 12.

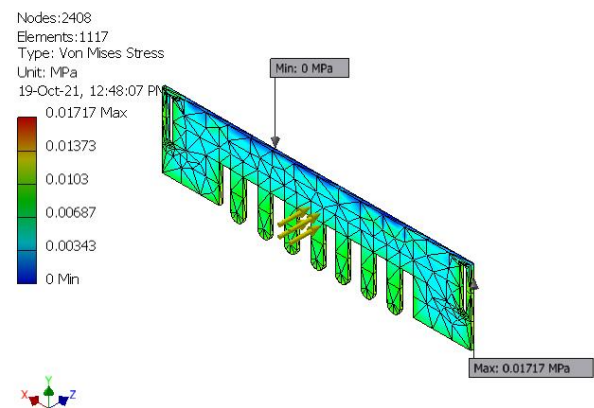


Figure 12. Von mises stress distribution on the machine's blade.

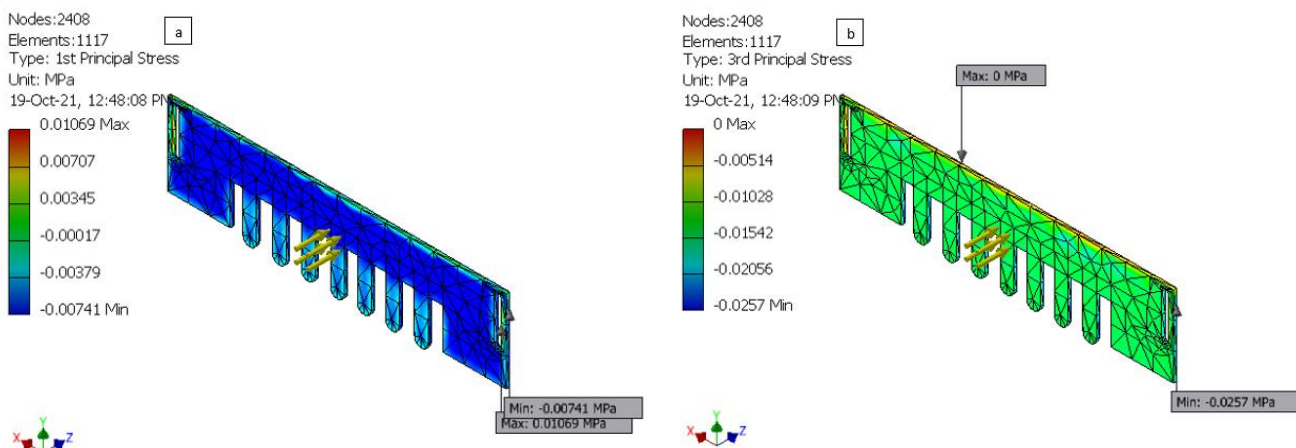


Figure 13. Principal stresses (a) first and (b) third.

Figure 12 illustrates the stress distribution on the machine blade under the applied loading conditions. A maximum von Mises stress of 0.01717 MPa is observed at the outer right

face of the blade, while negligible (approximately zero) stress is recorded at the upper face. The extremely low maximum stress value indicates that the blade operates well within safe

limits during both idle and service conditions, as it is significantly lower than the material's yield strength of 207 MPa and ultimate tensile strength of 345 MPa. This large margin confirms that the blade is not susceptible to yielding or fracture under the applied loading conditions.

The distributions of the first and third principal stresses on the blade are presented in Figure 13. These principal stress values further confirm the structural integrity of the blade, as their maximum magnitudes remain far below the yield and ultimate strength limits of the blade material. Consequently, the blade is expected to maintain structural stability throughout its operational lifespan without the risk of plastic deformation.

The deformation responses of the blade in the x-, y-, and z-directions are shown in Figure 14. The maximum deformation values of 1.78×10^{-7} mm, 1.715×10^{-7} mm, and

3.213×10^{-7} mm were recorded in the x, y, and z directions, respectively. These maximum deformations occur at the blade tip, a region prone to stress concentration due to continuous shredding and threshing actions during operation. Despite this localized deformation, the magnitude remains negligible, indicating elastic behavior and confirming the ductile nature of the blade material under service conditions. No evidence of plastic deformation is observed.

Further validation of blade safety was conducted using the safety analysis module within Autodesk Inventor, with the results presented in Figure 15. A minimum safety factor of 15 was obtained, demonstrating a substantial safety margin against failure. This high safety factor confirms the suitability of the selected blade material and geometry for the intended shredding and threshing applications, ensuring reliable performance without the risk of plastic failure during service.

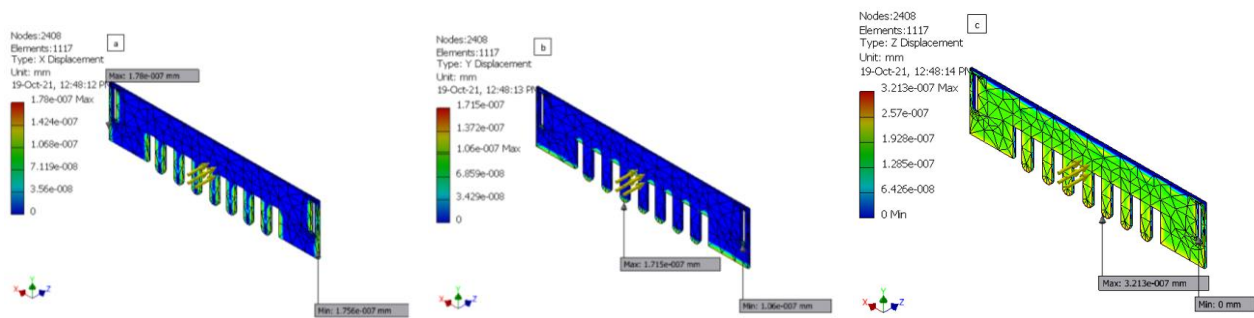


Figure 14. Deformations produced on the blade in the (a) x-direction, (b) y-direction, and (c) z-direction.

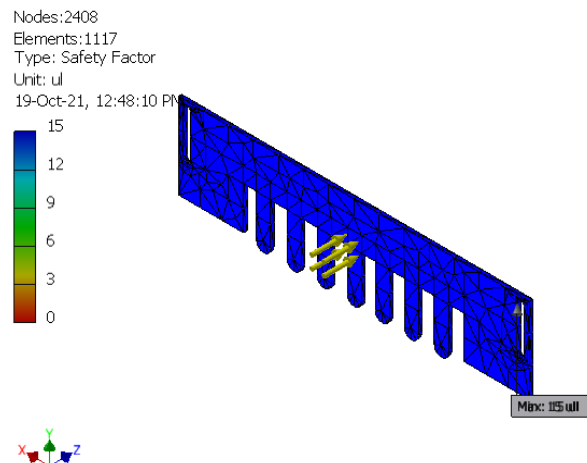


Figure 15. Blade's safety analysis.

3.3. Virtual Simulation Result of the Main Shaft and Tray of the Machine

The motions of the main shaft and tray during the shredding and threshing operation were simulated, and the result is presented in Figure 16.

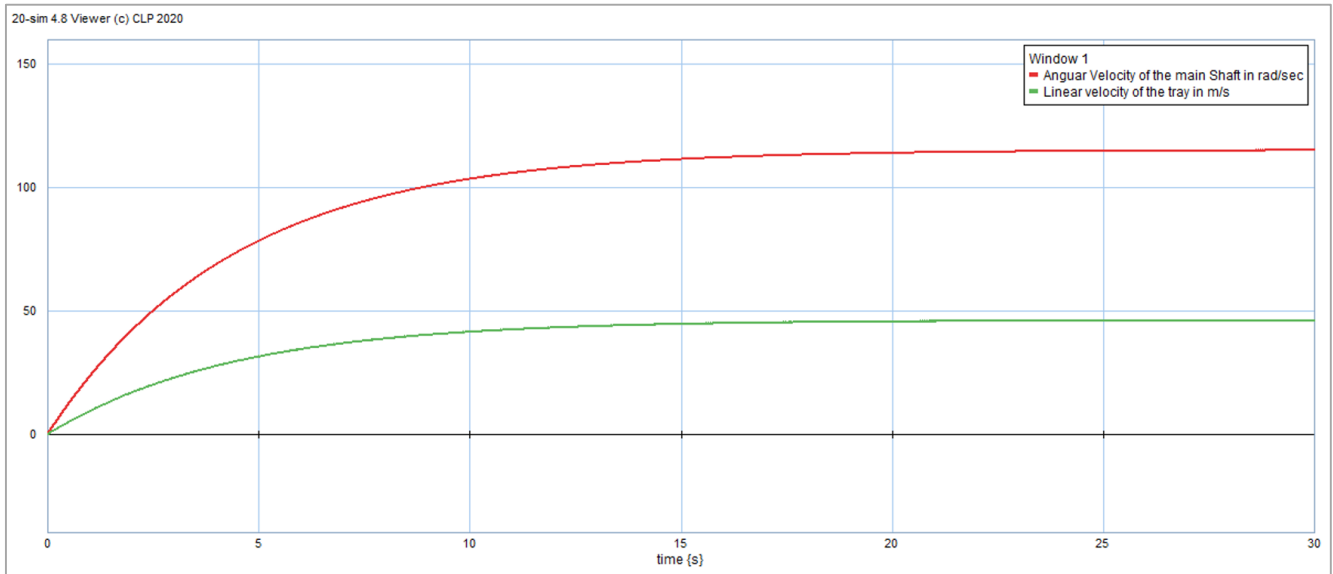


Figure 16. Simulation graph of the main shaft and tray motions.

Analysis of the motion characteristics presented in Figure 16 indicates that the tray operates at a lower linear velocity compared to the angular velocity of the main shaft. As time progresses, both the tray linear speed and the shaft angular speed increase steadily and proportionally. This acceleration phase continues until approximately 20 seconds, after which both velocities attain steady-state conditions and remain constant throughout operation. Under normal operating conditions, the machine functions at a linear speed of approximately 48 m/s for the tray and an angular speed of about 120 rad/s for the main shaft. The proportional and synchronized progression of these velocities demonstrates a well-coordinated motion profile, which is indicative of optimal dynamic performance of the universal shredding and threshing machine. The observed velocity characteristics are significant, as stable and consistent speeds are critical for ensuring smooth and efficient shredding and threshing operations. The relatively higher angular speed of the main shaft facilitates effective rotation and impact action required for shredding and threshing, while the comparatively lower linear speed of the tray enables controlled and uniform material conveyance. This balance minimizes material accumulation, reduces vibration, and enhances process stability. Overall, the attainment of steady-state speeds and the coordinated motion behavior of the tray and shaft confirm that the machine is properly designed and calibrated for efficient operation. These performance characteristics support reliable material processing, improved operational efficiency, and enhanced productivity, thereby validating the suitability of the universal shredding and threshing machine for sustained agricultural and industrial applications.

4. Conclusions

Based on the systematic design, construction, and perfor-

mance evaluation of the universal shredding and threshing machine, the following key conclusions are drawn:

- 1) **Optimal Operational Performance:** The machine exhibited a high operational efficiency of approximately 90%, demonstrating its effectiveness in executing shredding and threshing operations. This performance level indicates efficient material processing with minimal losses, confirming the suitability of the design for agricultural applications.
- 2) **Structural Integrity of the Frame:** Finite element analysis (FEA) of the machine frame confirmed its structural adequacy under both idle and operational conditions. No evidence of plastic deformation or structural failure was observed. The maximum shear stress recorded in the frame was 0.3004 MPa, which is significantly lower than the yield strength (207 MPa) and ultimate tensile strength (345 MPa) of the frame material. A maximum displacement of 0.01293 mm occurred at the lower section of the frame supporting the threshing shaft and blade assembly, a value well within permissible limits. The evaluated reaction forces and moments further validated the frame's ability to withstand imposed operational loads.
- 3) **Suitability of the Blade Material:** The structural analysis of the blade material confirmed its reliability and safety for shredding and threshing operations. The maximum von Mises stress experienced by the blade was 0.01717 MPa, which is negligible compared to the material's yield and ultimate strengths of 207 MPa and 345 MPa, respectively. Deformation values in all principal directions were minimal, indicating adequate ductility and resistance to plastic deformation under service conditions. The computed safety factor of 15 further underscores the blade material's suitability for sustained operation in both idle and service modes.

- 4) Motion and Dynamic Performance: Motion simulation of the main shaft and tray revealed proportional and stable dynamic behavior during operation. Both components exhibited a progressive increase in speed until stabilizing at approximately 20 seconds. The tray operated at a linear speed of about 48 m/s, while the main shaft achieved an angular speed of approximately 120 rad/s. This synchronized and stable motion confirms efficient power transmission and optimal dynamic performance of the machine during shredding and threshing operations.

Overall, the comprehensive analytical and simulation-based evaluation demonstrates that the universal shredding and threshing machine meets its design objectives in terms of efficiency, structural integrity, material suitability, and dynamic performance. These findings validate the machine's effectiveness and reliability for shredding and threshing applications across a range of agricultural processing conditions.

Abbreviations

CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
FEA	Finite Element Analysis
RPM	Revolution Per Minute
HP	Horse Power

Conflicts of Interest

The authors declare no conflicts of interest.

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