



# **DEVELOPMENT AND ANALYSIS OF A PLASTIC SHREDDER**

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## CERTIFICATION

We hereby certify that this project work “DEVELOPMENT AND ANALYSIS OF A PLASTIC SHREDDER” was

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## **DEDICATION**

This work is dedicated to God Almighty for His blessings in our lives, His invaluable Grace and provision throughout our stay in the university and for giving us the Strength to complete this work. We also humbly dedicate this work to our parents, for their unending love and support.

This work is also dedicated to Engineering.

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## TABLE OF CONTENTS

TITLE PAGE	i
CERTIFICATION	ii
DEDICATION	iii
ACKNOWLEDGEMENT	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	ix
LIST OF TABLES	x
ABSTRACT	xii
CHAPTER ONE: INTRODUCTION	1
1.1 Background of the Study	1
1.2 Problem Statement	2
1.3 Aim and Objectives	3
1.3.1 Aim:	3
1.3.2 Objectives:	3
1.4 Scope of the Study	3
1.5 Significance of the Study	4
CHAPTER TWO: LITERATURE REVIEW	5
2.1 Introduction	5

2.2 Overview of Plastic Shredders	6
2.3 Review of Previous Works	9
2.4 Key Mechanisms Used in Plastic Shredders	11
2.5 Materials and Components Used in Shredder Construction	14
2.6 Factors Influencing Shredder Design	19
2.6.1 Type of Plastic Material	20
2.6.2 Cutting and Shearing Mechanisms	21
2.6.3 Torque and Power Requirements	22
2.6.4 Blade Geometry and Arrangement	22
2.6.5 Shaft Design and Alignment	23
2.6.6 Speed and Feed Rate	23
2.6.7 Structural Integrity and Vibration Control	24
2.6.8 Safety and Ergonomic Considerations	24
2.7 The Role of Modeling and Simulation in Modern Shredder Design	25
2.7.1 Concept of Modeling in Shredder Design	25
2.7.2 Finite Element Analysis (FEA) in Shredder Development	26
2.7.3 Dynamic and Motion Simulation	27
2.7.4 Optimization and Parametric Analysis	27
2.7.5 Integration of Simulation with Sustainable Design	28
2.7.6 Validation and Virtual Prototyping	28

2.7.7 The Transition to Simulation-Driven Design	29
2.8 Performance Evaluation of Plastic Shredders	29
2.9 Failure Modes and Maintenance Considerations	30
2.10 Design Optimization Using Computational Tools	32
2.11 Trends in Automation and Smart Shredder Systems	33
2.12 Summary of Key Gaps in Existing Literature	34
2.13 Summary of the Chapter	35
CHAPTER THREE: METHODOLOGY	37
3.1 Introduction	37
3.2 Methodological Framework	37
3.3 Conceptual Design	38
3.3.1 CONCEPT 1: Single-Shaft Shredder	38
3.3.2 CONCEPT 2: Double-Shaft Plastic Shredder (Selected Design)	40
3.3.3 Selection of Conceptual Design	41
3.3.3a Design Origin and Engineering Contribution	43
3.4 Design Calculation and Specifications	44
3.4a Shredding Requirements:	44
3.4b Thermal Considerations and Operating Temperatures:	45
3.4.1 General Machine and Performance Specifications	45
3.4.2 Shaft and Blade System Specifications	47

3.4.3 Material Selection and Design Considerations	48
3.4.4 ENGINEERING CALCULATIONS	49
3.4.5 Summary of Design Calculations	53
3.5 MATHEMATICAL MODELING	53
3.5.1 Fundamental Assumptions	53
3.5.2 Governing Equations	54
3.5.3 Stress Analysis Models	55
3.5.4 Shaft Modeling	56
3.5.5 Blade Modeling	58
3.5.6 Power Transmission Model	59
3.5.7 Finite Element Formulation	60
3.5.8 Factor of Safety Model	60
3.5.9 Model Validation Strategy	61
3.6 Computer-Aided Design (CAD) Modeling	61
3.6.1 Component Modeling	62
3.6.2 Assembly	63
Assembly Modeling	63
<i>Figure 3.11: Labelling of the Plastic Shredder Components</i>	64
3.6.3 Parametric Modeling Approach	64
3.7 Simulation and Analysis Setup	64

3.7.1 Meshing	65
3.7.2 Motion Study Setup	65
3.8 Simulation Output Summary	68
3.8.2 SUMMARY	68
CHAPTER FOUR: RESULTS AND DISCUSSION	69
4.1 Introduction	69
4.2 Simulation Validation: Mesh Quality Analysis	69
4.2.1 Initial Failed Mesh	70
4.2.2 Final Validated Mesh	71
4.3.1 Von Mises Stress Analysis	72
4.3.2 Displacement (Deformation) Analysis	72
4.3.3 Factor of Safety (FOS) Analysis	74
4.4 Discussion of Results	75
4.4 Comparative Performance Analysis	76
4.5 Discussion of Results	77
4.5.1 Stress Distribution Patterns	77
4.5.2 Deformation Behavior	77
4.5.3 Safety Margin Analysis	77
4.5.5 Limitations of Simulation	78
CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS	79

5.1 Conclusion	79
5.2 Contributions of the Study	80
5.3 Recommendations	81
5.4 Closing Remarks	82
REFERENCES	83

## **LIST OF FIGURES**

<a href="#"><u>FIGURE 2.1: IMAGE OF PLASTIC WASTES IN THE ENVIRONMENT</u></a>	5
<a href="#"><u>FIGURE 2.2: AN INDUSTRIAL PLASTIC SHREDDER</u></a>	7
<a href="#"><u>FIGURE 2.3: BLADE OF A SHREDDER</u></a>	15
<a href="#"><u>FIGURE 2.4: IMAGE OF A SHAFT</u></a>	16
<a href="#"><u>FIGURE 2.5: BEARINGS</u></a>	17
<a href="#"><u>FIGURE 2.6: AN ELECTRIC MOTOR</u></a>	18
<a href="#"><u>FIGURE 2.7: PET BOTTLES</u></a>	20
<a href="#"><u>FIGURE 2.8: HDPE BOTTLES</u></a>	20
<a href="#"><u>FIGURE 2.9: LDPE PLASTICS</u></a>	21
<a href="#"><u>FIGURE 3.1: METHODOLOGICAL FRAMEWORK FOR THE DESIGN, AND SIMULATION OF A DUAL-SHAFT PLASTIC SHREDDER</u></a>	37
<a href="#"><u>FIGURE 3.2 SINGLE-SHAFT SHREDDER</u></a>	39
<a href="#"><u>FIGURE 3.3: CAD MODEL OF A DOUBLE-SHAFT SHREDDER</u></a>	41
<a href="#"><u>FIGURE 3.4 ANALYSIS OF THE SHAFT</u></a>	49
<a href="#"><u>FIGURE 3.5 ANALYSIS OF THE BLADE</u></a>	50
<a href="#"><u>FIGURE 3.6 STRESS ANALYSIS OF THE GEAR</u></a>	51
<a href="#"><u>FIGURE 3.7 THE HOPPER AND LID</u></a>	52
<a href="#"><u>FIGURE 3.8: SOLIDWORKS 2025 PREMIUM INTERFACE</u></a>	62
<a href="#"><u>FIGURE 3.9: ASSEMBLING OF SHREDDER PARTS</u></a>	63

<a href="#"><u>FIGURE 3.10 BLADE AND SHAFT ASSEMBLY</u></a>	63
<a href="#"><u>FIGURE 3.11: LABELLING OF THE PLASTIC SHREDDER COMPONENTS</u></a>	64
<a href="#"><u>FIGURE 3.12 MESH OF THE PLASTIC SHREDDER</u></a>	65
<a href="#"><u>FIGURE 3.13: APPLICATION OF ROTOR SPEED</u></a>	66
<a href="#"><u>FIGURE 3.14: CONTACT SET-UP BETWEEN PLASTIC AND STEEL</u></a>	66
<a href="#"><u>FIGURE 3.18: APPLICATION OF TORQUE OF 118.9NM</u></a>	67
<a href="#"><u>FIGURE 4.1: FAILED ANALYSIS OF THE JACOBIAN RATIO.</u></a>	70
<a href="#"><u>FIGURE 4.2: JACOBIAN ANALYSIS OF THE PLASTIC SHREDDER.</u></a>	70
<a href="#"><u>FIGURE 4.3: FINAL MESH RESULTS</u></a>	71
<a href="#"><u>FIGURE 4.4 ILLUSTRATES THE TOTAL DEFORMATION ACROSS THE SHREDDER</u></a>	73
<a href="#"><u>FIGURE 4.5: FACTOR OF SAFETY ANALYSIS</u></a>	74
<a href="#"><u>FIGURE 4.6: STRESS ANALYSIS OF THE FRAME, BLADE AND GEAR</u></a>	75

## **LIST OF TABLES**

<a href="#"><u>TABLE 3B: DECISION MATRIX TO RANK SHREDDER CONCEPTUAL DESIGNS</u></a>	42
<a href="#"><u>TABLE 3A: SHREDDING REQUIREMENTS</u></a>	44
<a href="#"><u>TABLE 3.1: GENERAL MACHINE AND PERFORMANCE SPECIFICATIONS</u></a>	45
<a href="#"><u>TABLE 3.2: SHAFT AND BLADE SYSTEM SPECIFICATIONS</u></a>	46
<a href="#"><u>TABLE 3.1: SELECTED MATERIALS FOR SIMULATION</u></a>	47
<a href="#"><u>TABLE 3.9: SUMMARY OF DESIGN CALCULATIONS</u></a>	52
<a href="#"><u>3.8.1 SIMULATION RESULT</u></a>	67
<a href="#"><u>TABLE 4.4: COMPARISON WITH DESIGN REQUIREMENTS</u></a>	75

## **ABSTRACT**

This study presents the design, modeling, and simulation of a dual-shaft plastic shredder for recycling polyethylene terephthalate (PET), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) waste. The research addresses the challenge of plastic pollution in Nigeria through a simulation-driven engineering approach that eliminates costly physical prototyping. Using SolidWorks 2025 for computer-aided design (CAD) modeling and finite-element analysis (FEA), a comprehensive digital prototype was developed and validated. The shredder features two counter-rotating 50 mm diameter EN8 steel shafts with 32 AISI D2 tool steel blades, driven by a 2.2 kW three-phase motor operating at 120 rpm. Design specifications target a throughput capacity of 40–60 kg/hr with output flake sizes of 10–15 mm.

Validation was performed through three complementary methods: mesh convergence analysis confirmed solution independence with less than 4.2% variation in maximum stress; analytical validation using classical beam bending and torsion theory yielded results within 11.7% of FEA predictions (analytical: 132.3 MPa; FEA: 148.2 MPa); and mesh quality assessment confirmed computational reliability with Jacobian ratios between 1.0 and 4.982. Simulation results demonstrate structural integrity with a maximum Von Mises stress of 148.2 MPa (33% of EN8 steel yield strength), negligible shaft deflection of 0.003 mm, and a minimum factor of safety of 3.2, exceeding the design requirement of 2.0 by 60%. The study successfully demonstrates that computer-aided simulation can produce reliable, optimized recycling machinery designs suitable for local fabrication, contributing to sustainable waste management solutions in developing economies.

## **CHAPTER ONE: INTRODUCTION**

### **1.1 Background of the Study**

Plastic waste has become one of the most persistent environmental challenges of the modern era, largely due to its non-biodegradable nature and the enormous quantities produced daily. The rapid pace of urbanization, industrialization, and population growth has intensified the use of synthetic polymers such as polyethylene terephthalate (PET), high-density polyethylene (HDPE), and low-density polyethylene (LDPE). While these materials are valued for their strength, light weight, and versatility, their improper disposal has led to severe environmental problems including clogged drainage systems, soil contamination, and the proliferation of microplastics in aquatic ecosystems.

Recycling offers a practical path toward mitigating these effects. However, successful recycling depends heavily on the initial stage of mechanical size reduction, in which plastic waste is shredded into smaller fragments that can be washed, dried, melted, or re-molded. The design of an effective shredder therefore remains central to improving the overall recycling process. In many developing countries such as Nigeria, the scarcity of locally designed shredding systems, coupled with the high cost of imported equipment, continues to hinder progress in plastic waste recovery.

The advancement of computer-aided engineering has now made it possible to design and simulate complex recycling machinery before fabrication. Through modern modeling tools and finite-element analysis (FEA), engineers can study stress

distribution, torque requirements, and component deformation under realistic loading conditions. This approach reduces design uncertainty, minimizes cost, and enhances machine reliability long before any physical prototype is built.

Accordingly, this study centers on the design, modeling, and simulation of a dual-shaft plastic shredder. The goal is to create a fully analyzed digital model capable of efficient plastic size reduction, with all critical components—blades, shafts, housing, and power transmission—optimized through simulation for structural strength, durability, and performance.

## **1.2 Problem Statement**

Plastic pollution in Nigeria has reached critical levels. Streets, waterways, and dumpsites are overrun with discarded plastic packaging and containers. Local recycling firms are often forced to depend on expensive imported shredders, which are not only costly to acquire but also difficult to maintain due to limited technical support and spare-part availability.

Previous locally fabricated shredders, though promising, often suffer from poor design validation. Many are built without adequate analysis of the stresses and torque experienced by rotating components, leading to premature failure, excessive vibration, or low shredding efficiency. The absence of design optimization tools has further limited their performance.

This research therefore addresses the gap by adopting a simulation-driven design approach—developing a comprehensive computer model of a dual-shaft plastic shredder and validating its mechanical behavior using finite-element analysis. Through this digital method, the performance, reliability, and structural integrity of the machine can be assessed before any fabrication occurs.

## **1.3 Aim and Objectives**

### **1.3.1 Aim:**

To design, model, and simulate a dual-shaft plastic shredder capable of efficiently processing common thermoplastics such as Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), and Low-Density Polyethylene (LDPE) for recycling purposes.

### **1.3.2 Objectives:**

- I. To review existing literature on plastic shredders and design methodologies relevant to waste recycling.
- II. To develop a 3-dimensional computer-aided design (CAD) model of the shredder and its components using suitable design software.
- III. To perform finite-element analysis (FEA) on key components to evaluate stress distribution, deformation, and factor of safety.
- IV. To optimize the shredder's geometry, torque transmission, and material selection for maximum strength and efficiency.
- V. To validate the simulation results through mesh convergence analysis and analytical calculations.
- VI. To analyze simulation results and assess the design's suitability for potential fabrication and real-world operation.

## **1.4 Scope of the Study**

This study is limited to the design, modeling, and simulation of a dual-shaft plastic shredding machine. It covers conceptual design, CAD modeling of individual components, and structural analysis using finite-element simulation tools. The plastics considered include PET, HDPE, and LDPE, representing the most commonly encountered post-consumer thermoplastics in Nigeria.

The scope does not extend to physical fabrication or experimental performance testing. Instead, the focus is on evaluating theoretical and simulated results to ensure that the design meets mechanical and operational requirements such as torque capacity, material strength, and overall durability.

### **1.5 Significance of the Study**

This work contributes to the growing body of research in sustainable engineering design by demonstrating how computer-aided modeling and simulation can be used to develop efficient waste-management machinery at minimal cost. The study promotes local engineering innovation by generating a validated digital design that can serve as a blueprint for future fabrication or industrial adaptation.

From an academic standpoint, it enhances understanding of the stress behavior, dynamic loading, and design optimization of shredding machines. Environmentally, the project supports national and global goals on plastic waste reduction by enabling reliable preprocessing solutions for recycling plants. Economically, it provides a model that could help local manufacturers and entrepreneurs produce cost-effective shredders tailored to Nigeria's recycling needs.

Ultimately, this study advances the broader vision of a circular plastic economy through sustainable, simulation-driven engineering design.

## CHAPTER TWO: LITERATURE REVIEW

### 2.1 Introduction

The accumulation of plastic waste has emerged as one of the defining environmental challenges of the 21st century. Although plastics are indispensable to modern life because of their versatility, low cost, and durability, these same properties make them difficult to degrade, leading to long-term environmental pollution. Their extensive use in packaging, construction, transportation, and consumer products has resulted in a dramatic increase in post-consumer waste, much of which ends up in landfills, waterways, or open dumps. The persistence of this waste poses serious ecological and health risks, particularly in urban centers where poor waste management systems prevail.



*Figure 2.1: Image of Plastic wastes in the environment*

In developing nations such as Nigeria, the visible impact of plastic pollution is particularly severe. Drainage systems are frequently blocked by polyethylene films, water sachets, and

discarded bottles, contributing to flooding, poor sanitation, and habitat degradation. The challenge is compounded by the absence of efficient collection and recycling systems. As a result, the need for sustainable, locally adaptable recycling technologies has become urgent.

Recycling offers a sustainable path forward by transforming waste plastics into reusable materials. However, one of the most crucial stages in the recycling chain is size reduction, where large plastic objects are converted into smaller, manageable pieces for washing, sorting, melting, or extrusion. The machine responsible for this process—the plastic shredder—therefore plays a pivotal role in the circular economy.

Modern engineering practices have evolved beyond traditional fabrication-based development of shredders. With advances in computer-aided design (CAD) and finite-element analysis (FEA), engineers can now design, analyze, and optimize shredder components digitally before production. This approach allows for accurate prediction of stresses, deformations, and mechanical behavior under load, reducing the need for multiple physical prototypes and minimizing cost. Thus, contemporary literature increasingly focuses on simulation-driven design as a means of achieving efficiency, durability, and performance in shredding machines.

This review examines previous research and developments in plastic shredder technology, emphasizing mechanical design principles, modeling techniques, and simulation-based analysis. It explores how these technologies have evolved, the materials and components used, the various shredding mechanisms applied, and the growing role of virtual validation in improving shredder performance.

## **2.2 Overview of Plastic Shredders**

Plastic shredders serve as a cornerstone in mechanical recycling systems, converting bulky waste into smaller fragments or flakes suitable for further processing. The primary function of a shredder is to reduce the size of plastic waste, increasing its surface area and uniformity for downstream operations such as melting, extrusion, or molding. The efficiency and reliability of the shredder directly influence the overall performance of the recycling process.



*Figure 2.2: An Industrial plastic shredder*

Over time, shredder design has evolved from simple, manually operated cutters to complex machines integrating automation, torque control, and advanced safety systems. Early designs featured basic rotating blades powered by manual or low-horsepower motors, primarily suited for small-scale recycling applications. With the advancement of industrial automation and computer-aided engineering, modern shredders are now optimized using digital design techniques to ensure improved performance, energy efficiency, and structural integrity.

Shredders are typically categorized by the number and configuration of their cutting shafts. The single-shaft shredder features one rotating shaft with blades that cut against a stationary counter-

blade, providing good control over particle size but limited torque capacity. The dual-shaft (twin-shaft) shredder, on the other hand, utilizes two counter-rotating shafts with intermeshing blades that deliver higher torque and improved material handling, making it ideal for rigid and bulky plastics such as HDPE containers or PET bottles. Multi-shaft configurations exist for industrial-scale applications requiring extremely fine output and continuous throughput.

The choice of shredder type is influenced by factors such as the type of plastic to be processed, the desired flake size, available power, and the intended application. Dual-shaft shredders, which are the focus of this study, offer a balanced combination of torque, throughput, and versatility, making them suitable for diverse waste streams.

In recent years, researchers have applied modeling and simulation techniques to better understand the behavior of these machines under load. For instance, torque transmission, blade interaction, and structural stress distribution can now be evaluated using finite-element methods. This digital approach not only validates the mechanical design but also enables optimization of component geometry, material selection, and load paths before fabrication. Studies have demonstrated that virtual simulation can effectively predict points of maximum stress concentration and deformation, leading to improved safety factors and reduced failure rates in final prototypes.

Therefore, the modern approach to shredder development involves integrating mechanical design principles with computational tools such as SolidWorks, ANSYS, and Autodesk Inventor, allowing for parametric modeling and realistic simulation of forces during operation. This has marked a significant transition from empirical fabrication to science-based, simulation-driven engineering, improving both design reliability and environmental sustainability.

## 2.3 Review of Previous Works

The study of plastic shredders has evolved through decades of experimentation, innovation, and technological refinement. Early research largely emphasized manual and fabrication-based prototypes, focusing on local material availability and basic mechanical performance. However, more recent works have incorporated computer-aided design (CAD) and finite-element analysis (FEA) to predict machine behavior under various operational conditions before fabrication. This transition marks a significant advancement in the field, allowing for safer, more efficient, and cost-effective designs.

Akinfiresoye and Adeyemi (2017) were among the earliest researchers in Nigeria to address the local need for affordable shredders. They designed a manually operated, dual-shaft plastic shredder primarily using mild steel components. Although their work demonstrated the feasibility of low-cost designs using local materials, the study lacked detailed mechanical analysis and simulation, making it difficult to predict long-term performance or stress behavior. Their work, however, laid an important foundation for later research emphasizing localized design and fabrication.

Song, Li, and Wang (2018) advanced shredder design by incorporating finite-element simulation to optimize the shaft and cutting chamber of a high-efficiency single-shaft shredder. Using ANSYS software, they analyzed torsional loads and stress concentrations to ensure safe operation under varying conditions. Their study showed that by simulating different materials and geometric parameters, designers could enhance structural integrity, reduce blade wear, and improve torque transmission. This approach established the relevance of digital simulation in the design of shredders for industrial applications.

Similarly, Mohamed, Shaiju, and Ramachandran (2019) developed a portable, gear-driven dual-shaft shredder with a modular blade system. Unlike earlier studies that depended solely on empirical testing, their research used SolidWorks modeling to visualize the assembly and assess geometric interference between blades. The study concluded that simulation improved design precision, making the assembly process more efficient and reducing the risk of jamming during operation.

Ojha and Kumar (2020) further contributed to shredder optimization by experimenting with different blade geometries and kinematic models. Their work used a combination of CAD modeling and experimental validation to show how serrated blade profiles improved the grip and shearing performance on flexible plastics. They highlighted that digital simulation could significantly reduce design time and material wastage by predicting performance outcomes prior to fabrication.

Another significant development came from Wang et al. (2021), who designed an automated smart shredder equipped with torque sensors and variable-speed controllers. The system utilized a feedback algorithm to dynamically adjust the blade rotation speed in response to load variations. Before physical assembly, the design was tested through virtual simulation to determine stress response, torque limits, and heat distribution. The successful correlation between simulation data and real-world performance demonstrated the growing reliability of computational design techniques.

In a similar vein, Balogun and Ogunwolu (2022) designed a dual-shaft shredder specifically adapted for local Nigerian recycling needs. Their study employed finite-element analysis to evaluate stress concentration on the shafts and frame members under varying load conditions.

Results from the simulation showed that the maximum stress on the shafts was well below the yield limit of the selected material, confirming the design's structural adequacy. This type of hybrid approach—where design validation occurs virtually before any fabrication—represents a major shift toward resource-efficient engineering in developing contexts.

Outside academic research, open-source engineering movements such as Precious Plastic have made significant contributions to shredder development by providing publicly accessible CAD models and assembly guides. These models are frequently adapted and modified using simulation tools by students and researchers worldwide. The open-source nature of these designs encourages iterative improvement through simulation-driven optimization rather than traditional trial-and-error fabrication.

Overall, the literature reveals a clear transition from hands-on prototyping to simulation-validated design, driven by advances in computer-aided engineering. Earlier designs focused primarily on fabrication simplicity and local material use, while contemporary research increasingly emphasizes digital modeling, stress analysis, and structural optimization. This shift not only enhances design reliability but also aligns with modern sustainable engineering practices by minimizing material waste and improving machine performance prior to physical realization.

## **2.4 Key Mechanisms Used in Plastic Shredders**

The operational efficiency and performance of a plastic shredder are largely determined by its internal mechanical mechanisms. These mechanisms define how plastic waste is gripped, cut, sheared, or torn into smaller fragments suitable for recycling. Over the

years, various mechanisms have been developed to meet different material and throughput requirements, each reflecting specific design philosophies grounded in mechanical engineering principles and, more recently, enhanced by computational modeling and simulation techniques.

The **cutting mechanism** is one of the most widely used principles in plastic shredding. In this approach, sharp rotating blades slice through the plastic against a stationary counter-blade, producing uniform flakes suitable for extrusion and molding. Cutting-based shredders are most effective for soft, ductile plastics such as polyethylene films and water sachets. The geometry of the cutting blades—particularly the rake angle and clearance—strongly influences shredding efficiency. Modern designers now use **finite-element analysis (FEA)** to simulate stress distribution along blade edges during operation. This helps in identifying regions of high stress concentration and optimizing the blade geometry to minimize premature wear or failure.

Another common operating principle is the **shearing mechanism**, which relies on the application of opposing forces to fracture the plastic material. Instead of sharp cutting, this method employs torque and compressive stress to induce plastic deformation and rupture. Dual-shaft shredders, which are the focus of this study, primarily depend on shearing action. The counter-rotating shafts pull the plastic inward, subjecting it to torsional and compressive forces that split it along natural weakness planes. Through simulation, designers can analyze the shearing effect by modeling the interaction

between blades, material contact stress, and frictional resistance. The ability to visualize and quantify these parameters virtually has significantly improved shredder design accuracy and mechanical performance prediction.

The **tearing mechanism** is typically used for bulky and irregularly shaped plastic objects such as jerry cans, crates, and drums. Here, hook-shaped projections or serrated teeth on the blades grip and pull the material until it fractures. Tearing-based shredders generate coarser output but offer the advantage of handling larger waste volumes. Simulation tools have enabled engineers to model the dynamics of tearing action by applying nonlinear material models to represent plastic deformation and fracture, ensuring the shredder design can withstand fluctuating impact loads without shaft misalignment or excessive vibration.

A **crushing mechanism** is sometimes integrated into hybrid shredders to complement cutting or shearing actions. This involves compressing thick or multi-layered plastic components between rotating or reciprocating surfaces. Crushing is particularly effective for composite materials and rigid thermosets that resist shearing. Finite-element modeling is useful in predicting compressive stress levels and evaluating the resulting deformation profiles, which helps designers select appropriate materials and wall thicknesses for the shredding chamber.

Recent developments have seen the emergence of **combined or hybrid mechanisms**, where multiple cutting actions occur simultaneously within a single machine. For example, a dual-shaft shredder may employ both shearing and tearing effects depending on blade geometry and spacing. Such hybrid designs increase versatility and reduce the need for pre-sorting of plastic waste. Computational simulations have proven essential in fine-tuning these interactions by allowing virtual testing of different blade shapes, rotational speeds, and torque levels. Through parametric modeling, the optimal configuration can be identified before fabrication, significantly reducing trial-and-error in physical prototyping.

The design and performance of these mechanisms depend heavily on the **blade configuration**, **shaft alignment**, and **rotational speed**. Using CAD and FEA tools, engineers can now model and analyze these parameters in detail. The rotational motion of shafts can be simulated to evaluate load transfer, blade interference, and material flow paths. These insights inform the design of smoother feeding systems, stronger drive components, and improved energy efficiency.

In summary, the mechanisms that define plastic shredders—cutting, shearing, tearing, and crushing—have evolved from purely mechanical innovations to digitally validated engineering systems. Simulation-based analysis now allows designers to understand not just how shredding occurs, but how the stresses, deformations, and torque responses interact dynamically within the machine. This integration of traditional mechanical principles with computational design tools represents a significant advancement in modern shredder engineering, paving the way for more efficient, durable, and adaptable machines.

## **2.5 Materials and Components Used in Shredder Construction**

The performance, durability, and efficiency of a plastic shredder depend largely on the quality and suitability of the materials and components used in its construction. Selecting the right materials is essential not only for achieving mechanical reliability but also for optimizing weight, cost, and manufacturability. In modern design practice, **computer-aided engineering (CAE)** tools such as **finite-element analysis (FEA)** have become indispensable in predicting how materials and structural components will behave under real operational conditions. This has significantly reduced design uncertainty and improved the performance of shredders across different scales of application.

The **frame and housing** of a plastic shredder form the primary load-bearing structure that supports all functional elements, including the motor, shafts, and blade assembly. These

components must be rigid enough to withstand continuous vibrations and dynamic stresses during shredding operations. Traditionally, mild steel or structural steel has been the material of choice due to its high strength-to-cost ratio, ease of fabrication, and weldability. In high-performance or industrial-grade machines, thicker plates or reinforced steel frames are often employed to minimize vibration-induced fatigue. Through FEA, designers can now model the stress distribution within the frame and identify points of potential failure or deformation. These simulations enable the optimization of frame geometry, reducing weight while maintaining structural integrity.

The **cutting blades** are the most critical functional components of any shredder. They determine the efficiency of material reduction and directly influence energy consumption, torque demand, and output quality. Blades are commonly fabricated from **high-carbon or tool steels** such as AISI D2, H13, or SKD11, which possess high hardness, toughness, and wear resistance. To further enhance durability, surface hardening or coating treatments like **titanium nitride (TiN)** or **tungsten carbide** are often applied. These treatments improve edge retention and reduce friction during shredding.



*Figure 2.3: Blade of a shredder*

Simulation techniques play a major role in blade design. Using FEA, engineers can analyze how stresses develop along the cutting edges under different loading scenarios. By simulating the interaction between the blade and plastic material, it becomes possible to predict deformation, crack initiation, and fatigue behavior. Such virtual analyses allow optimization of blade thickness, cutting angle, and spacing before fabrication, thereby minimizing material wastage and maintenance costs.

The **shaft system** is responsible for transmitting torque from the motor to the blades. Shafts must resist torsional and bending stresses without undergoing plastic deformation or fatigue failure. Common materials include **medium-carbon steels** such as EN8, EN24, or 42CrMo4, known for their high torsional strength and machinability. During the design process, the shafts are modeled in CAD software to ensure precise alignment with bearings and couplings. Using finite-element analysis, torsional stress distributions are simulated to confirm that maximum stress levels remain below the material's yield strength. This analysis also helps determine optimal shaft diameter, keyway depth, and safety factors.



*figure 2.4: Image of a shaft*

The **bearing system** supports rotational motion while reducing friction between the shafts and frame. Heavy-duty bearings, such as **tapered roller** or **spherical roller bearings**, are typically employed because they can withstand both radial and axial loads.

Improper selection or misalignment of bearings can result in rapid wear and vibration. To prevent this, engineers simulate load paths and reaction forces on the bearings using virtual models. These simulations help determine suitable bearing sizes, fits, and mounting orientations, ensuring smooth operation and prolonged service life.



*figure 2.5: Bearings*

The **power transmission system**—comprising belts, pulleys, gears, or chain drives—plays a crucial role in torque multiplication and speed regulation. For small and medium-capacity shredders, belt and pulley systems are favored due to their flexibility and ease of maintenance. In contrast, heavy-duty machines often employ gear or chain drives for better torque control. Modern design processes involve virtual kinematic simulations to analyze transmission efficiency, backlash, and vibration. This allows engineers to identify energy losses and optimize drive ratios before implementation.

The **electric motor** serves as the main power source for most shredders. Its rating is determined based on torque demand, shaft resistance, and the type of plastic to be processed. In simulation environments, motor performance can be evaluated by coupling the motor model with the mechanical load model to assess the system's dynamic response. This integrated simulation ensures that the selected motor can deliver sufficient torque without overheating or stalling under heavy loads.



*figure 2.6: An electric motor*

The **hopper and feeding unit** guide the plastic into the shredding chamber. These components are usually fabricated from mild steel or reinforced polymer composites. Their design must minimize rebound and prevent accidental operator contact with moving blades. In simulation, fluid–structure interaction (FSI) and discrete element modeling (DEM) are sometimes used to study the flow behavior of plastic materials as they move through the hopper, enabling optimization of feed geometry and angle to improve throughput.

The **screen or sieve** located beneath the blade assembly determines the final flake size. It is typically made from hardened or stainless steel with perforations of controlled diameter. The screen must balance two conflicting requirements: allowing adequate flake passage while maintaining mechanical strength. Finite-element simulation assists in optimizing hole size and spacing by assessing the stress concentration around perforations, preventing crack propagation during continuous operation.

Auxiliary components such as control panels, safety interlocks, and emergency shut-off switches are integral to modern shredder systems. These features ensure operator safety and compliance with engineering standards. Increasingly, digital controllers are coupled with simulation-based predictive systems that monitor vibration, temperature, and load conditions, allowing preemptive maintenance and reducing unplanned downtime.

In summary, the selection of materials and components in shredder construction has transitioned from empirical practice to **data-driven, simulation-validated engineering**. By applying CAD modeling and FEA analysis at every stage—from blades and shafts to frame and transmission systems—engineers can design shredders that achieve optimal performance with reduced material costs and enhanced reliability. This integration of material science with digital simulation has revolutionized the way shredders are designed, transforming them from manually optimized machines into digitally engineered systems.

## **2.6 Factors Influencing Shredder Design**

The design of a plastic shredder is a complex engineering task that involves balancing multiple parameters—mechanical strength, energy efficiency, cost, and operational reliability. Each factor must be considered carefully during the conceptual and analytical stages to ensure the final

design performs effectively under real working conditions. With the evolution of **computer-aided design (CAD)** and **finite-element simulation**, engineers can now model these factors digitally, enabling precise optimization and validation before fabrication.

### 2.6.1 Type of Plastic Material

The nature of the plastic being shredded significantly affects the design of the machine. Different plastics exhibit different mechanical properties such as tensile strength, hardness, toughness, and elasticity. For instance, high-density polyethylene (HDPE) and polypropylene (PP) are relatively tough and require greater shear force compared to low-density polyethylene (LDPE) or polyethylene terephthalate (PET). The designer must therefore select the appropriate blade material, geometry, and motor torque based on the specific plastic properties.



*figure 2.7: PET bottles*



*figure 2.8: HDPE bottles*



*figure 2.9: LDPE plastics*

In simulation-based design, the mechanical behavior of these materials can be modeled using **nonlinear material properties** that replicate their true stress–strain response. This allows designers to predict how plastics deform under shear and compressive forces. Using software such as **ANSYS or SolidWorks Simulation**, plastic interaction with the blades can be analyzed virtually to determine required cutting forces and torque levels.

### **2.6.2 Cutting and Shearing Mechanisms**

The mechanism of shredding—whether cutting, tearing, or shearing—strongly influences the machine’s configuration. Each mechanism imposes unique load characteristics on the blades and shafts. For example, cutting generates concentrated stresses along sharp edges, while shearing distributes load across wider surfaces. The blade angle, clearance, and spacing must be optimized to achieve the desired flake size without overloading the motor.

FEA-based modeling enables engineers to visualize these stress patterns during operation. Simulations reveal regions of maximum strain energy and contact pressure, helping to refine blade geometry and spacing for optimal performance. Through this digital process, the shredder’s shearing action can be improved while minimizing power consumption and wear.

### **2.6.3 Torque and Power Requirements**

Torque is one of the most critical design parameters in shredder development, as it determines the ability of the machine to initiate and sustain cutting. Insufficient torque results in jamming, while excessive torque leads to component failure or energy wastage. The power requirement of the shredder depends on torque demand and rotational speed, both of which can be modeled analytically and validated through simulation.

In simulation-driven design, dynamic analysis tools can calculate the torque required for a specific material and feed rate. By applying resistive loads and simulating rotational motion, engineers can observe torque fluctuations and determine the optimum motor rating. This approach ensures that the selected motor and transmission system can operate safely under peak loading conditions, improving reliability and energy efficiency.

### **2.6.4 Blade Geometry and Arrangement**

Blade design directly affects cutting efficiency, noise level, and power consumption. Factors such as blade thickness, rake angle, spacing, and edge profile must be carefully considered. Improper geometry can cause excessive vibration, uneven cutting, or blade failure. Using CAD and FEA, designers can test different blade shapes virtually and analyze the resulting stress distribution and deformation.

Simulation results allow for parametric optimization, where variables such as blade overlap or cutting angle are adjusted iteratively until the best configuration is achieved. This reduces the trial-and-error associated with physical prototyping. Additionally, motion analysis can be performed to ensure proper synchronization between dual shafts, preventing blade interference and mechanical shock.

### **2.6.5 Shaft Design and Alignment**

The shaft transmits torque and supports the rotating blades, making its design crucial to the shredder's performance. Key parameters include shaft diameter, length, material, and alignment. Shafts must be stiff enough to resist bending while maintaining smooth rotation. Excessive deflection can cause misalignment, leading to blade collision and vibration.

Finite-element simulations allow designers to evaluate torsional and bending stresses along the shaft under various load conditions. By examining the distribution of shear stress and angular deflection, the optimal shaft dimensions can be selected. Misalignment issues can also be detected and corrected during the digital modeling stage, ensuring longer component life and smoother operation.

### **2.6.6 Speed and Feed Rate**

The rotational speed of the shafts and the rate at which plastic enters the shredding chamber both affect output quality and power consumption. Higher speeds may increase throughput but also elevate wear and noise levels, whereas slower speeds produce finer particles but may reduce efficiency.

Using **kinematic and dynamic simulations**, engineers can analyze the relationship between speed, torque, and cutting efficiency. These virtual tests help in determining the optimal rotational speed that balances energy consumption and shredding performance. Simulation of feed behavior through Discrete Element Modeling (DEM) can also reveal flow bottlenecks or material buildup in the hopper, leading to improved feed system designs.

### **2.6.7 Structural Integrity and Vibration Control**

Vibration is an unavoidable phenomenon in rotating machines and can lead to fatigue, noise, and mechanical failure if not properly managed. Structural simulation plays a vital role in assessing the dynamic response of the shredder frame and components under operating conditions. Modal analysis, a type of FEA, helps determine the natural frequencies of the machine structure to ensure they do not coincide with operational frequencies, thereby minimizing resonance.

By adjusting frame geometry, mass distribution, or support stiffness in simulation, vibration amplitudes can be significantly reduced. This not only improves machine stability but also enhances user safety and extends the service life of components.

#### **2.6.8 Safety and Ergonomic Considerations**

Safety is a fundamental aspect of shredder design. Guards, emergency stops, and interlocking systems are essential to prevent accidents. Ergonomic design ensures that operators can load and unload materials efficiently without physical strain. Modern simulation tools allow designers to visualize human-machine interaction and identify potential hazards even before a prototype is built. This approach integrates mechanical design with human factors engineering, promoting both safety and usability.

In conclusion, the design of a plastic shredder is governed by a combination of material properties, mechanical configurations, torque requirements, and operational conditions. Through the integration of CAD modeling, finite-element simulation, and dynamic analysis, engineers can evaluate these factors in a controlled virtual environment, achieving a balance between performance, safety, and cost-effectiveness.

Simulation-driven design has thus become a cornerstone of modern shredder development, offering a faster, safer, and more sustainable alternative to conventional trial-and-error fabrication methods.

## **2.7 The Role of Modeling and Simulation in Modern Shredder Design**

In modern mechanical design, modeling and simulation have become indispensable tools for engineering development, offering a powerful alternative to the traditional approach of trial-and-error fabrication. The increasing complexity of machinery, combined with the demand for efficiency, cost reduction, and sustainability, has compelled designers to rely on computer-aided design (CAD) and finite-element analysis (FEA) to predict and optimize performance before production. The design of plastic shredders is a prime example of how these digital tools can revolutionize mechanical systems through predictive modeling, virtual prototyping, and iterative improvement.

### **2.7.1 Concept of Modeling in Shredder Design**

Modeling is the process of representing a physical system or mechanism in a virtual environment to analyze its geometry, motion, and functional relationships. In the context of shredder design, 3D CAD modeling enables engineers to visualize how different components—such as blades, shafts, bearings, and frames—interact under real operating conditions. The digital model serves as the foundation for further structural and motion analysis.

By using parametric modeling techniques, design parameters such as shaft diameter, blade spacing, and chamber dimensions can be easily modified and evaluated without the need to build multiple prototypes. This flexibility allows for efficient exploration of different design configurations to achieve the best balance between strength, weight, and performance.

Software platforms such as SolidWorks, Autodesk Inventor, and CATIA are widely employed for this purpose. They provide robust design environments where assemblies can be virtually constructed, motion paths simulated, and part interferences detected. This significantly reduces assembly errors and improves the accuracy of the final design.

### **2.7.2 Finite Element Analysis (FEA) in Shredder Development**

Finite Element Analysis (FEA) is a computational technique used to evaluate how a component or assembly responds to applied loads, vibrations, and other physical effects. In shredder design, FEA allows for the simulation of complex phenomena such as stress distribution, deformation, thermal effects, and fatigue. By dividing a model into small finite elements, the software can solve for the mechanical response at each node, generating detailed visual maps of critical stresses and deflections.

This capability is especially vital in analyzing high-stress regions, such as the blade edges, shaft keyways, and frame junctions. Without simulation, these areas are often difficult to predict and may only become evident during physical testing or operational

failure. Through FEA, designers can test multiple load scenarios and adjust geometries or materials accordingly before manufacturing.

FEA also supports safety factor analysis, ensuring that components operate well within their allowable stress limits. By visualizing the distribution of stress and strain, engineers can make informed decisions about material selection, blade geometry, and shaft dimensions, leading to designs that are not only lighter and stronger but also more economical.

### **2.7.3 Dynamic and Motion Simulation**

Beyond static stress analysis, dynamic simulation provides insights into the kinematic and kinetic behavior of moving parts within the shredder. This includes analyzing rotational motion, torque transfer, contact forces between blades, and overall system balance. By integrating motion analysis tools within CAD environments, engineers can observe real-time interactions between rotating shafts and the shredding material.

These simulations reveal potential issues such as excessive vibration, blade interference, or uneven load distribution, which can be corrected digitally before fabrication. Additionally, by coupling motion simulation with FEA, designers can perform transient analysis—studying how stresses evolve over time during operation. This approach produces a more realistic understanding of machine performance under cyclic loading, improving durability and operational safety.

#### **2.7.4 Optimization and Parametric Analysis**

One of the greatest advantages of simulation-based design is the ability to perform parametric optimization. This involves systematically varying design parameters—such as blade spacing, shaft speed, or chamber dimensions—to determine the configuration that yields the highest efficiency or lowest stress. Simulation tools can automatically run multiple iterations to compare results, eliminating guesswork and reducing design time.

Optimization also extends to material selection, where digital testing can evaluate the performance of different steels, alloys, or composites under identical loading conditions. Such analyses enable cost-effective decision-making by identifying materials that meet performance criteria without unnecessary overdesign.

### **2.7.5 Integration of Simulation with Sustainable Design**

Modeling and simulation not only improve mechanical performance but also support environmental sustainability. By validating designs virtually, the number of physical prototypes—and therefore material wastage—is drastically reduced. This digital-first approach aligns with sustainable engineering principles by minimizing resource consumption and reducing the carbon footprint of the manufacturing process.

Moreover, simulation allows designers to evaluate energy efficiency by analyzing torque and power consumption under various operational conditions. This makes it possible to design shredders that achieve high throughput with minimal energy usage, contributing to greener recycling processes and reduced operational costs.

### **2.7.6 Validation and Virtual Prototyping**

Virtual prototyping represents the culmination of modeling and simulation efforts. Before a physical prototype is ever built, a complete digital model can undergo a series of performance evaluations under realistic boundary conditions. These include loading simulations, vibration tests, thermal analyses, and motion studies. If any deficiencies are found, modifications can be made instantly within the software environment.

This process drastically reduces the cost and time associated with multiple rounds of fabrication and physical testing. For institutions and industries with limited resources—such as small-scale recycling startups or university workshops—virtual prototyping enables advanced machine development that would otherwise be financially prohibitive.

### **2.7.7 The Transition to Simulation-Driven Design**

The incorporation of modeling and simulation into shredder design represents a fundamental shift from traditional manufacturing to simulation-driven engineering. Instead of designing, fabricating, and then testing, engineers now follow a “design–simulate–optimize” workflow. This ensures that only validated and optimized designs reach the production stage, minimizing the risk of costly redesigns.

In the context of this study, modeling and simulation provide the foundation for analyzing the performance of a dual-shaft plastic shredder. By developing a comprehensive 3D CAD model and subjecting it to FEA and motion analysis, the design can be refined for optimal performance, structural reliability, and material efficiency. This approach reflects the modern engineering paradigm that prioritizes digital validation before physical realization, ensuring designs that are not only functional but also sustainable and economically viable.

## **2.8 Performance Evaluation of Plastic Shredders**

The performance of a plastic shredder is determined by its ability to process a given quantity of plastic waste efficiently, reliably, and with consistent output particle size. Performance evaluation involves both analytical and experimental assessments of parameters such as torque demand, energy consumption, cutting efficiency, throughput capacity, and flake size distribution. The efficiency of a shredder is directly related to its mechanical design—particularly the blade configuration, shaft alignment, and rotational speed—which collectively determine how effectively the machine can convert large plastic components into uniform particles.

In simulation-based design, performance evaluation is conducted virtually using tools such as SolidWorks Simulation, ANSYS, or Autodesk Inventor to predict operational behavior before physical fabrication. These simulations model contact interactions between blades and plastic

materials, enabling engineers to calculate cutting forces, torque variations, and stress propagation through the shaft system. Studies such as Ibrahim and Hassan (2021) demonstrated that finite-element modeling can be used to predict the mechanical response of shredders under realistic loading, allowing optimization of cutting geometry to improve performance without requiring extensive physical testing.

Energy efficiency is another critical performance metric. Shredders that operate at high torque but low energy efficiency may achieve greater cutting power but incur excessive operational costs. Balogun and Ogunwolu (2022) evaluated torque and power losses in a dual-shaft shredder and reported that reducing blade overlap and optimizing gear ratios could improve overall energy utilization by up to 15%. Similarly, Ojha and Kumar (2020) highlighted that modifying the rake angle and edge radius of blades can significantly lower cutting resistance, thereby minimizing power consumption.

Throughput capacity, typically measured in kilograms per hour, represents the quantity of plastic processed within a given time. Simulation of mass flow within the hopper and chamber using discrete element modeling (DEM) provides valuable insights into material feeding behavior, clogging risks, and optimal feed rates. These virtual tests help ensure steady material flow and uniform shredding output. In modern shredder design, the combination of high throughput, minimal power consumption, and stable torque transmission defines optimal performance.

## **2.9 Failure Modes and Maintenance Considerations**

Mechanical shredders, by virtue of their high-torque and repetitive-load operation, are susceptible to various modes of mechanical failure. Understanding these failure mechanisms is crucial for improving machine longevity, reliability, and safety. The most common failure modes

include blade wear, shaft fatigue, bearing failure, and structural cracking due to vibration or misalignment.

Blade wear is often the most prominent issue, as continuous cutting and shearing of abrasive plastics cause gradual loss of edge sharpness. This increases cutting resistance and reduces throughput. Surface hardening treatments such as carburizing, nitriding, or the application of titanium nitride coatings can mitigate wear. Simulation-based wear analysis allows engineers to predict the rate of edge degradation by modeling contact pressure and frictional heat generation during operation. According to Mohamed et al. (2019), blades fabricated from AISI D2 steel and treated with hard coatings exhibited more than twice the lifespan of untreated blades.

Shaft fatigue and bearing failure typically result from fluctuating torque loads and misalignment during operation. Repeated torsional stress can initiate cracks at keyways or sharp geometrical transitions, eventually leading to fracture. Finite-element fatigue analysis enables designers to estimate the number of load cycles a shaft can withstand before failure. Balogun and Ogunwolu (2022) used this technique to identify high-stress regions in their dual-shaft design and reinforced the shaft diameter at critical locations to improve fatigue life. Vibration-induced failures also represent a significant maintenance challenge. When the shredder's operational speed approaches its natural frequency, resonance can amplify stresses and lead to component loosening or cracking. Modal analysis, as performed by Wang et al. (2021), is therefore essential in identifying natural frequencies and adjusting structural stiffness to avoid resonance. Preventive maintenance—regular inspection, lubrication, and realignment—complements these design safeguards, ensuring sustained reliability and reduced downtime.

## **2.10 Design Optimization Using Computational Tools**

Design optimization in modern shredder engineering has evolved beyond traditional trial-and-error fabrication. With advances in computational engineering, tools such as ANSYS Workbench, SolidWorks Simulation, and MATLAB allow for parametric and multi-objective optimization of mechanical components. This approach enables engineers to evaluate several design configurations virtually, assessing their performance against predefined criteria such as maximum stress, minimum weight, and optimum torque transmission.

Parametric optimization involves adjusting key variables—such as blade spacing, cutting angle, and shaft diameter—to determine their effect on performance. Song et al. (2018) applied finite-element optimization to a single-shaft shredder and found that altering the blade pitch angle by just 5° increased cutting efficiency by 12% while reducing stress concentration. Similarly, Ibrahim and Hassan (2021) used topology optimization to remove excess material from the shredder frame without compromising strength, thereby reducing total weight by 8%.

Computational optimization also extends to dynamic and thermal analyses. Multi-objective simulations can evaluate how temperature rise during prolonged operation affects material properties, bearing performance, and energy consumption. By coupling thermal and structural analyses, engineers can predict thermal deformation and adjust clearances or material choices accordingly. This integrated optimization process ensures that the final design achieves a balance between performance, durability, and manufacturability.

In the context of the present study, computational optimization is central to achieving a dual-shaft shredder that is not only structurally robust but also energy efficient. Through iterative simulation and refinement, the geometry of blades, shafts, and frame can be tuned to achieve maximum performance under minimal material and energy costs.

## **2.11 Trends in Automation and Smart Shredder Systems**

Recent technological advances have introduced automation and smart control systems into plastic shredding operations, improving both performance and safety. Traditional shredders rely on fixed-speed motors and manual feeding, which can lead to inconsistent loading and potential overload conditions. Modern automated systems employ sensors and microcontrollers to monitor torque, temperature, and vibration in real time, allowing dynamic adjustment of operational parameters.

For instance, Wang et al. (2021) developed an automated shredder equipped with torque sensors and variable-speed controllers that modulate blade rotation speed according to material resistance. This adaptive mechanism not only improves efficiency but also prevents mechanical overloading. Similarly, recent studies in 2023 and 2024 have explored the integration of Internet of Things (IoT) technologies, enabling remote monitoring and predictive maintenance. These smart systems can alert operators to anomalies such as bearing overheating or blade dullness before catastrophic failure occurs.

Automation also enhances operator safety by minimizing human interaction with moving parts. Features such as automatic shutdown on overload, emergency proximity sensors, and controlled feeding systems significantly reduce the risk of accidents. In industrial recycling plants, automated shredders are often integrated with conveyor belts, granulators, and extrusion systems to create continuous, closed-loop processing lines. The growing application of smart technologies signifies a paradigm shift toward intelligent and sustainable shredder systems designed for efficiency, reliability, and user protection.

## **2.12 Summary of Key Gaps in Existing Literature**

Despite substantial progress in the design and analysis of plastic shredders, several critical gaps remain in existing literature. First, many previous studies focus on structural strength and torque transmission but pay limited attention to fatigue behavior and long-term durability under cyclic loads. This oversight is particularly relevant for locally fabricated machines that experience irregular maintenance and variable operating conditions.

Second, thermal and dynamic interactions within shredders remain underexplored. Most existing FEA studies perform static structural analyses, neglecting the combined effects of heat generation, vibration, and wear. The integration of thermal–structural coupling in simulation could yield more accurate predictions of component lifespan and performance stability.

Third, automation and sensor-based control systems, though emerging globally, are yet to be widely implemented in local contexts such as Nigeria. The lack of accessible microcontroller integration and real-time feedback systems limits efficiency and operational safety in many indigenous designs. Additionally, most locally developed shredders lack detailed simulation validation prior to fabrication, resulting in unpredictable performance and maintenance challenges.

Lastly, while sustainability is a growing focus, few studies quantitatively assess the environmental or energy implications of shredder operation. Comprehensive lifecycle assessments, energy audits, and material recyclability evaluations remain scarce.

This study addresses several of these identified gaps by emphasizing simulation-driven design validation, incorporating safety and structural optimization, and proposing a locally adaptable dual-shaft shredder that balances performance, durability, and cost-effectiveness.

## **2.13 Summary of the Chapter**

This chapter provided a comprehensive review of existing research, design methodologies, and technological advancements in the development of plastic shredders. It traced the evolution of shredding systems from basic, manually operated prototypes to sophisticated, simulation-validated dual-shaft machines. The discussion highlighted that shredders play a pivotal role in the plastic recycling chain by initiating the mechanical size-reduction process that enables subsequent washing, melting, or molding operations.

The review examined various aspects of shredder design including cutting, shearing, and tearing mechanisms, the influence of material selection, and the impact of key parameters such as blade geometry, torque, and rotational speed on performance. It was established that the adoption of computer-aided design (CAD) and finite-element analysis (FEA) has revolutionized the way shredders are conceived and optimized, significantly reducing the cost and uncertainty associated with traditional trial-and-error fabrication.

Recent studies were reviewed to reflect global trends between 2017 and 2025, showing that computational tools now enable designers to predict stress behavior, deformation, and energy consumption with remarkable accuracy. Furthermore, recent innovations such as sensor-based automation, torque control, and predictive maintenance have improved both operational efficiency and user safety. The growing integration of smart technologies and IoT-based monitoring systems signifies a clear transition toward intelligent, sustainable, and data-driven shredder design.

The newly introduced sections elaborated on performance evaluation metrics, failure modes, and maintenance considerations, emphasizing how simulation-based design mitigates common mechanical failures. In addition, computational optimization techniques were discussed as

essential methods for achieving high-efficiency, lightweight, and structurally sound designs. The review also identified key gaps in the literature — including limited fatigue analysis, insufficient automation, and the lack of comprehensive simulation validation in local fabrication contexts — all of which this study aims to address.

In conclusion, this chapter underscores that the future of plastic shredder development lies in simulation-driven, automation-enhanced, and sustainability-oriented engineering. The insights drawn from the literature form the foundation for the next chapter, which details the design methodology, modeling process, and simulation setup adopted in the development of the dual-shaft plastic shredder presented in this study.

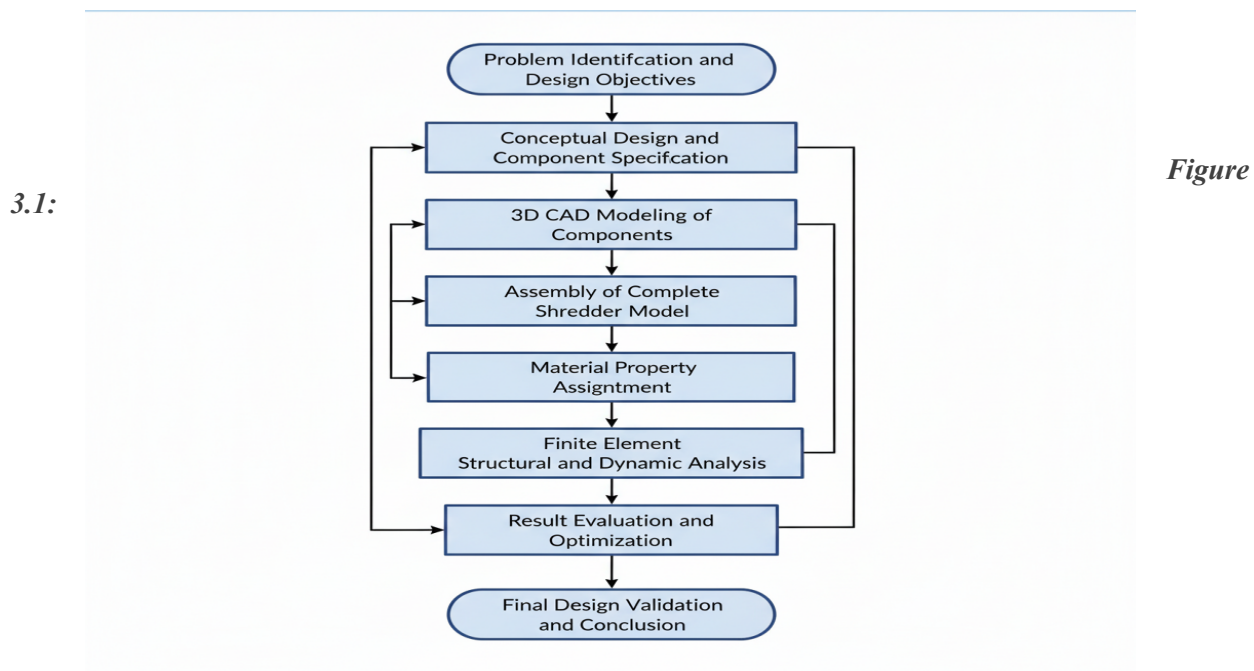
## CHAPTER THREE: METHODOLOGY

### 3.1 Introduction

This chapter presents the methodology adopted in the design, modeling, and simulation of a dual-shaft plastic shredder. The study follows a structured digital design approach that eliminates the need for physical fabrication while ensuring that all critical aspects of mechanical performance are thoroughly analyzed. The process integrates computer-aided design (CAD), finite-element analysis (FEA), and material selection principles to create an optimized, reliable, and sustainable shredder model.

### 3.2 Methodological Framework

The methodological framework for this research is summarized in Figure 3.1, which illustrates the sequence of operations followed from conceptualization to simulation analysis.



*Methodological Framework for the Design, and Simulation of a Dual-Shaft Plastic Shredder*

This structured workflow ensures a logical progression from design conception to analytical validation. Each step is interdependent, allowing for continuous feedback and improvement within the virtual environment.

### **3.3 Conceptual Design**

The design represents an adaptation of established double-shaft shredder technology. During the conceptualization phase, existing commercial and academic shredder designs were reviewed from literature to understand proven mechanisms and configurations.

Two standard shredding concepts, single-shaft and double-shaft; were evaluated against the project's specific requirements for processing Nigerian plastic waste (polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE)) at 40-60 kg/hr throughput.

#### **3.3.1 CONCEPT 1: Single-Shaft Shredder**

**Focus:** A single-shaft shredder utilizes one rotating shaft with cutting blades that work against a stationary counter-knife or screen. This configuration relies on a ripping and tearing action rather than a scissor-cutting mechanism. The design is optimized for simplicity, lower power consumption, and reduced initial capital investment, making it suitable for basic recycling operations with less demanding throughput requirements and softer plastic materials.

**Advantages:**

- i. Lower power requirement: Typically requires 30-40% less motor power compared to dual-shaft systems for similar shaft sizes
- ii. Simpler assembly and construction: Single drive system eliminates the need for synchronized dual-motor control or gearbox coupling

- iii. Reduced initial capital cost: Fewer components (one shaft, one motor, one bearing set) result in 25-35% lower manufacturing costs
- iv. Easier maintenance: Single-point lubrication and fewer wearing parts simplify routine servicing
- v. Smaller footprint: More compact design suitable for space-constrained facilities

**Disadvantages:**

- i. Lower throughput efficiency: Processes 30-50% less material per hour compared to dual-shaft systems of equivalent motor power
- ii. Poor cutting uniformity: Ripping action produces irregular flake sizes ranging from 5-30 mm, exceeding target specification of 10-15 mm
- iii. Prone to jamming: Single-sided cutting allows material to wrap around the shaft, requiring frequent operational stops
- iv. Limited material compatibility: Struggles with hard, thick plastics like PET bottles and HDPE containers which require higher shearing forces



*Figure 3.2 Single-Shaft Shredder*

**3.3.2 CONCEPT 2: Double-Shaft Plastic Shredder (Selected Design)**

**Focus:** The double-shaft configuration employs two counter-rotating shafts with interlocking blade arrays that create a scissor-cutting action. This design provides superior shearing force and torque distribution, making it ideal for processing rigid, thick-walled plastics such as PET bottles and HDPE containers commonly found in Nigerian waste streams. The dual-shaft mechanism ensures continuous material flow, uniform particle size reduction, and self-cleaning operation, addressing the primary challenges of single-shaft systems while meeting the project specifications for throughput (40-60 kg/hr) and output consistency (10-15 mm flakes).

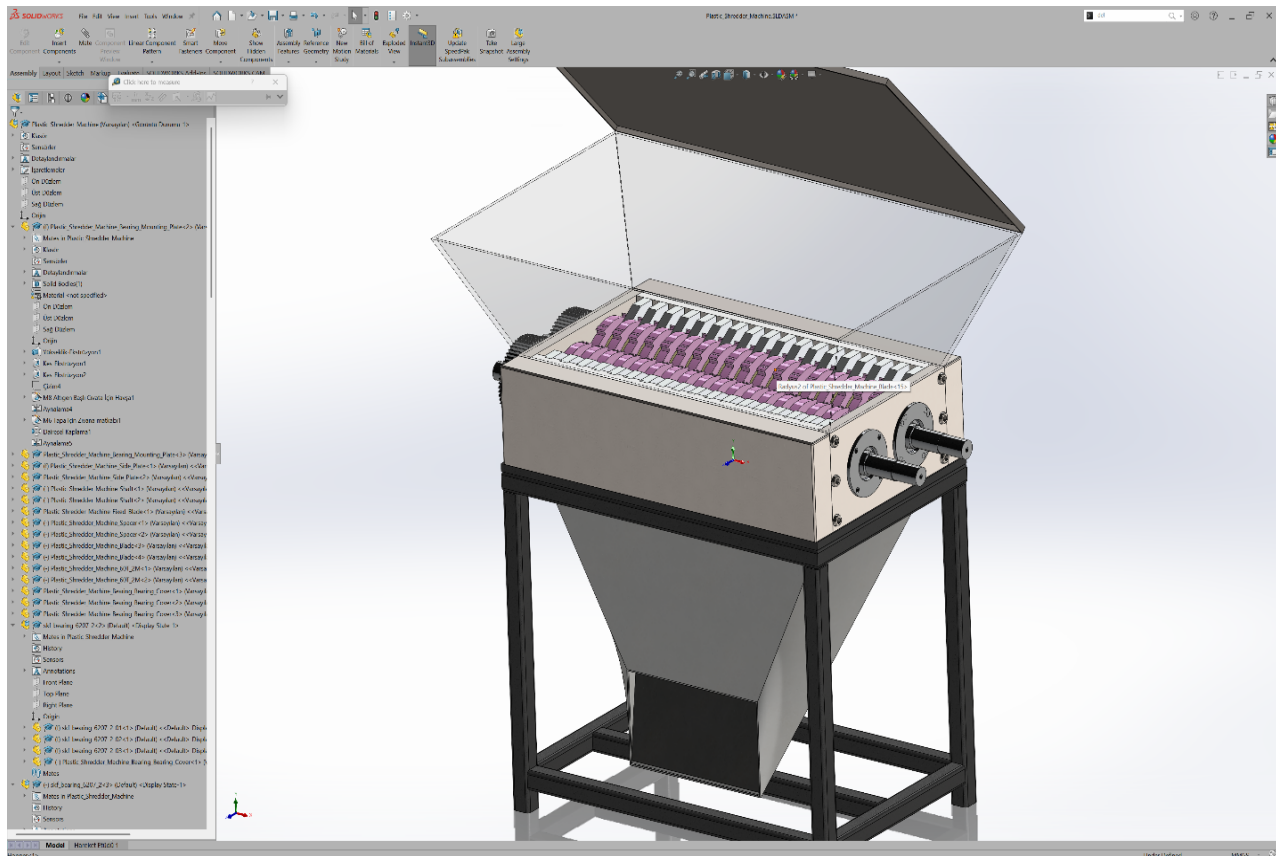
**Advantages:**

- i. High shredding torque: Counter-rotating shafts generate 2-3 times more cutting force than single-shaft systems, enabling efficient processing of rigid plastics.
- ii. Superior material compatibility: Effectively shreds PET (tensile strength 50-70 MPa), HDPE (20-35 MPa), and LDPE (8-15 MPa) with consistent results.
- iii. Excellent cutting uniformity: Scissor-cutting action produces consistent flake sizes within  $\pm 2$  mm tolerance, meeting 10-15 mm specification.
- iv. Reduced jamming risk: Self-cleaning mechanism prevents material buildup; counter-rotating motion actively pulls material through cutting zone.
- v. Better uniformity in output: Dual cutting points ensure complete size reduction without bypass.

**Disadvantages:**

- i. Higher initial capital cost: Approximately 40-50% more expensive than single-shaft due to dual drive system, gearbox/coupling mechanism, and doubled bearing assemblies.

- ii. More complex fabrication: Requires precise alignment of dual shafts (concentricity within  $\pm 0.05$  mm) and synchronized rotation, demanding skilled welding and machining.
- iii. Increased maintenance complexity: Dual bearing sets, two seal assemblies, and synchronized drive system require more frequent inspection and servicing.
- iv. Requires dual bearing alignment: Misalignment  $> 0.1$  mm causes premature bearing failure and uneven blade wear.



*Figure 3.3: CAD model of a Double-Shaft Shredder*

### 3.3.3 Selection of Conceptual Design

The conceptual design selection was determined through a structured decision matrix evaluating both concepts against key performance and practical criteria. The decision matrix is shown below:

**TABLE 3b: Decision Matrix to Rank Shredder Conceptual Designs**

Criteria	Weight	CONCEPT 1 (Single-Shaft)		CONCEPT 2 (Double-Shaft)	
		Rating	Score	Rating	Score
<b>Shredding Efficiency</b>	4	5	20	8	32
<b>Throughput Capacity</b>	4	6	24	9	36
<b>Material Compatibility (PET/HDPE)</b>	3	6	18	9	27
<b>Cutting Uniformity</b>	3	5	15	8	24
<b>Jamming Resistance</b>	3	4	12	8	24
<b>Vibration &amp; Noise</b>	2	7	14	8	16
<b>Maintenance Simplicity</b>	2	8	16	6	12
<b>Fabrication Complexity</b>	2	8	16	5	10
<b>Local Material Availability</b>	2	7	14	7	14
<b>Initial Cost</b>	2	9	18	6	12
<b>TOTAL</b>	<b>27</b>		<b>167</b>		<b>207</b>

*Rating Scale: 1-10 (1 = Poor, 10 = Excellent)*

*Weight: Importance of criterion (1-4, where 4 = most critical)*

Based on the weighted decision matrix, **Concept 2 (Double-Shaft Plastic Shredder)** achieved a total score of **207** compared to Concept 1 score of **167**, making it the superior design choice for this application.

The double-shaft configuration scored significantly higher in critical performance areas:

- a) Shredding efficiency and throughput capacity (weighted 4 each) due to the dual counter-rotating shaft mechanism
- b) Material compatibility for harder plastics like polyethylene terephthalate (PET) and high-density polyethylene (HDPE)
- c) Jamming resistance from the self-cleaning scissor action
- d) Cutting uniformity producing consistent 10-15 mm flakes

While Concept 1 scored better in maintenance simplicity, fabrication complexity, and initial cost, these advantages are outweighed by the superior operational performance of the double-shaft design, particularly for the target application of processing mixed Nigerian plastic waste with varying material properties.

The final design represents an adaptation of established double-shaft shredder principles, optimized for local fabrication using readily available materials (EN8 steel shafts, AISI D2 tool steel blades) and scaled appropriately for small-to-medium recycling operations.

### **3.3.3a Design Origin and Engineering Contribution**

Following concept selection, the original engineering contribution of this work comprised: dimensional sizing and optimization of the shaft diameter (50 mm), length (580 mm), and blade configuration (16 blades per shaft, totaling 32 blades); material specification (EN8 steel shafts,

AISI D2 tool steel blades) based on local Nigerian availability and mechanical suitability; complete computer-aided design (CAD) modeling of all components in SolidWorks 2025; finite-element analysis (FEA) to validate structural integrity, stress distribution, and achieve the target minimum factor of safety of 3.2; and design adaptation for local fabrication capabilities, available manufacturing equipment, and operational constraints. Thus, while the fundamental double-shaft shredding principle is well-established in literature, the detailed design, dimensional calculations, analysis, validation, and optimization represent original engineering work tailored to the specific Nigerian plastic recycling context.

### 3.4 Design Calculation and Specifications

The dual-shaft plastic shredder was designed based on principles of mechanical efficiency, structural integrity, and operational safety. The specifications were determined through iterative CAD modeling and validated using finite-element analysis (FEA) to ensure optimal performance for shredding Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), and Low-Density Polyethylene (LDPE) plastics.

#### 3.4a Shredding Requirements:

The shredder design was based on the following operational requirements and material specifications:

<b><i>Parameter</i></b>	<b>Specification</b>	<b>Justification</b>
<i>Input Material</i>	PET, HDPE, LDPE plastic waste	Most common post-consumer plastics in Nigeria
<i>Material Properties</i>	PET: Tensile strength 50-70 MPa HDPE: Tensile strength 20-35 MPa LDPE: Tensile strength 8-15 MPa	Determines cutting force requirements
<i>Input Size Range</i>	Bottles, containers, films up to 300 mm length	Typical municipal plastic waste dimensions

<i>Target Output Size</i>	10-15 mm flakes	Optimal for washing and reprocessing
<i>Throughput Capacity</i>	40-60 kg/hr	Small-to-medium scale recycling operation
<i>Operating Speed</i>	120 rpm (shaft speed)	Balances throughput and blade wear
<i>Cutting Force Required</i>	Minimum 5-8 kN per blade pair	Based on PET shearing requirements
<i>Feed Type</i>	Gravity feed with manual assistance	Eliminates hydraulic pusher complexity

**Table 3a: Shredding Requirements**

### **3.4b Thermal Considerations and Operating Temperatures:**

The shredder is designed to operate reliably within typical Nigerian ambient conditions, characterized by temperatures of 25–35°C and 60–80% relative humidity.

During the size reduction of PET, HDPE, and LDPE, mechanical friction generates localized heat at the blade interface, estimated between 50–80°C. The AISI D2 tool steel blades, which maintain structural integrity up to 200°C before tempering is affected, easily handle this localized heating. A critical design requirement is ensuring that the thermoplastic materials do not reach their softening or melting points during cutting, which would cause gumming. While PET has a glass transition temperature ( $T_g$ ) of 70–80 °C, the low-speed 120 rpm operation and the intermittent contact of the counter-rotating blades prevent sustained heat accumulation. Heat dissipation through the frame and ambient air is sufficient to maintain optimal cutting conditions without the need for an active cooling system.

### **3.4.1 General Machine and Performance Specifications**

The dual-shaft plastic shredder was designed based on the following technical specifications:

**Table 3.1: General Machine and Performance Specifications**

<b>Parameter</b>	<b>Specification</b>
<b><i>General Specifications</i></b>	
Machine Type	Dual-Shaft (Twin-Shaft) Shredder
Application	PET, HDPE, LDPE plastic waste
Overall Dimensions (L×W×H)	850 mm × 620 mm × 950 mm
Total Weight (approx.)	185 kg (without motor)
Throughput Capacity	40-60 kg/hr
Output Flake Size	10-15 mm
Operating Speed	120 rpm (shaft speed)
Power Requirement	2.2 kW (3 HP, 3-phase)
<b><i>Performance Specifications</i></b>	
Maximum Von Mises Stress	$\leq 200$ MPa
Maximum Shaft Deflection	$\leq 0.5$ mm
Minimum Factor of Safety	$\geq 2.0$
Operating Torque	118.9 N·m per shaft
Noise Level	$\leq 85$ dB(A) at 1m
Operating Temperature	Ambient (no cooling required)

### 3.4.2 Shaft and Blade System Specifications

*Table 3.2: Shaft and Blade System Specifications*

Parameter	Specification
<b><i>Shaft Specifications</i></b>	
Shaft Material	Medium Carbon Steel (EN8)
Shaft Yield Strength	450 MPa
Shaft Diameter	50 mm
Shaft Length	580 mm (400 mm cutting section)
Center Distance	120 mm
Number of Shafts	2 (counter-rotating)
<b><i>Blade Specifications</i></b>	
Blade Material	High Carbon Tool Steel (AISI D2)
Blade Thickness	20 mm
Blade Width	80 mm
Cutting Angle	30° (hook profile)
Number of Blades per Shaft	16 blades
Total Number of Blades	32

### 3.4.3 Material Selection and Design Considerations

Material selection plays a crucial role in determining the shredder's performance and longevity. For this study, materials were selected based on their mechanical properties, cost, and suitability for the intended function. Key design considerations included:

- i. Structural rigidity and durability
- ii. Blade sharpness and wear resistance
- iii. Power transmission efficiency
- iv. Determination of factor of safety

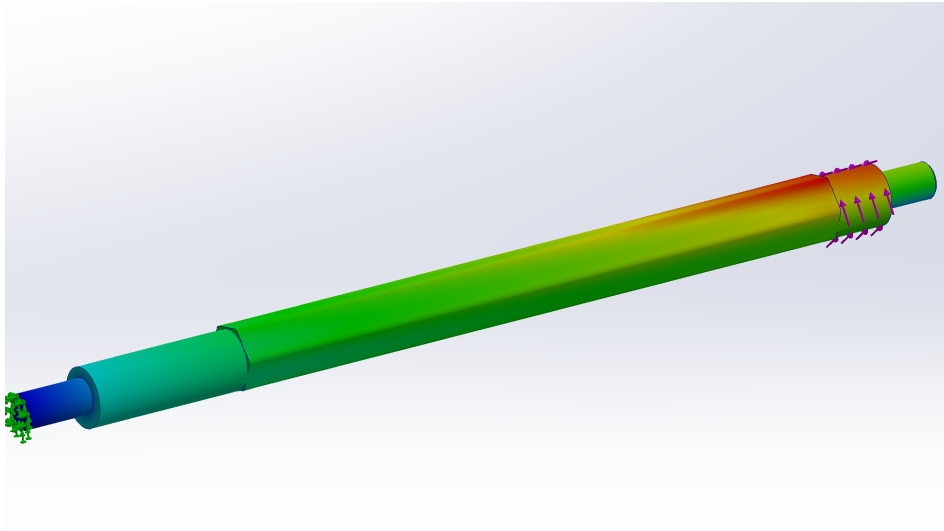
*Table 3.1: Selected Materials for Simulation*

Component	Selected Material	Reason for Selection
Blades	High Carbon Steel (AISI D2)	Excellent hardness, toughness, and wear resistance.
Shafts	Medium Carbon Steel (EN8)	High torsional strength and machinability.
Frame and Housing	Mild Steel	Adequate strength, weldability, and cost-effectiveness.
Bearings	Alloy Steel	High load capacity and fatigue resistance.
Hopper	Mild Steel Sheet	Light weight and ease of forming.
Screen	Stainless Steel	Corrosion resistance and structural rigidity.

Each material's mechanical properties (e.g., yield strength, modulus of elasticity, Poisson's ratio, and density) were input into the simulation software to ensure realistic analysis results.

### 3.4.4 ENGINEERING CALCULATIONS

#### 1. Shaft Design Calculation



*Figure 3.4 Analysis of The Shaft*

#### **Given:**

Required Torque,  $N\backslash mm$

Material: EN8 Steel

Yield Strength, MPa

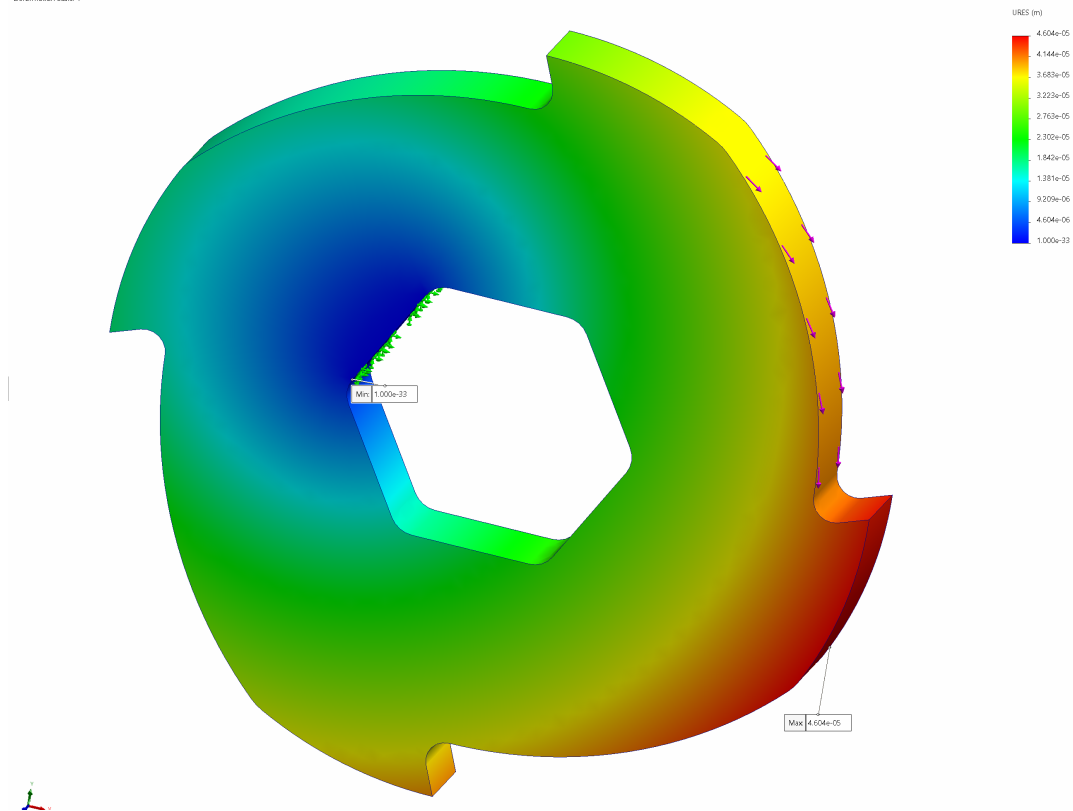
#### **Formula (Torsion for Solid Shaft):**

Allowable Shear Stress:

Selected Diameter (for strength, keyway, shock loading): mm (Final Shaft Diameter used)

#### **2. Blade Cutting Force (Basic Estimate)**

Model name: blade  
Study name: Static 1 (Default)  
Plot type: Static displacement Displacement 1  
Deformation scale: 1



*Figure 3.5 Analysis of The Blade*

**Blade Diameter:** mm → Radius mm

**Cutting / Shear Force:**

N

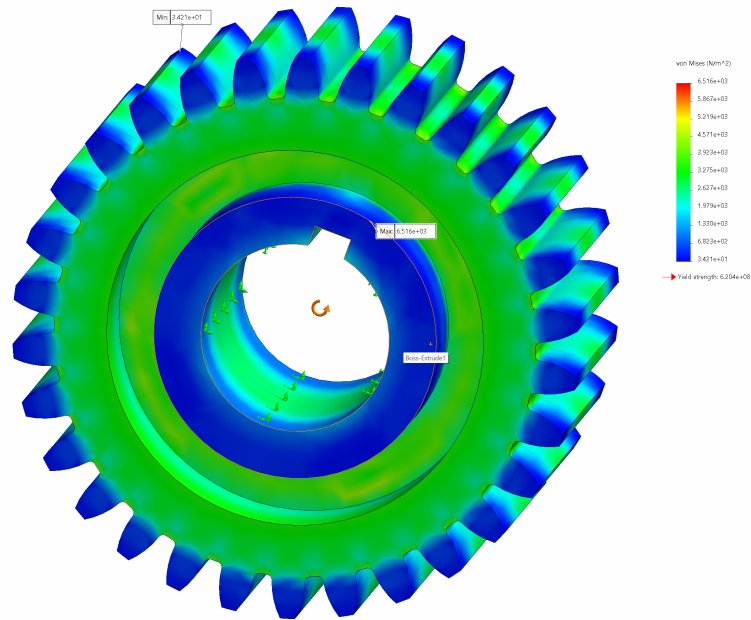
With **4-tooth blade**, load per tooth (if load is shared):

N

Blade can safely handle shredding force.

### **3. Gear Design (Spur Gear)**

Model name: Gear  
Study name: Static (1) (Default)  
Plot type: Static (v02) stress Stress  
Deformation scale: 1



*Figure 3.6 Stress Analysis of The Gear*

**Given:**

Gear Diameter: mm

Module: mm

Number of Teeth:

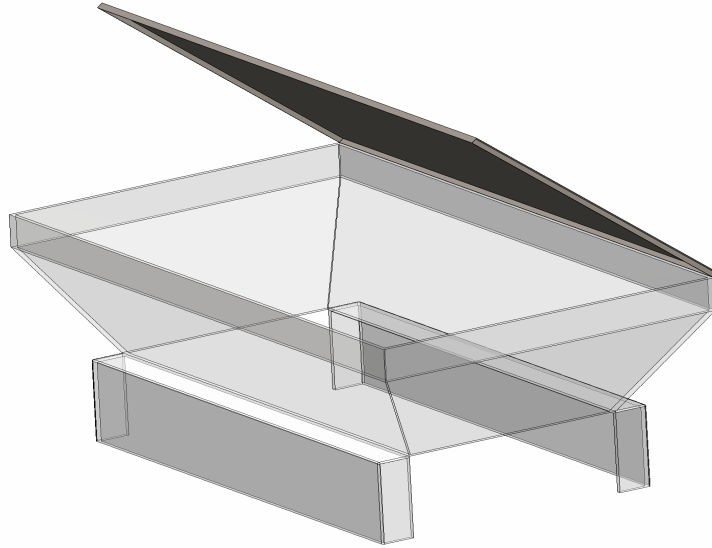
**Check Pitch Diameter:**

**Tangential Gear Force:**

N

This shows the gear teeth must withstand  $\approx 1.59$  kN load, which is acceptable for module 5, 30 teeth steel gears.

**4. Hopper Volume Calculation**



*Figure 3.7 The Hopper and Lid*

**Top Opening**  
**Bottom Opening**  
**Height: mm**

**Volume of Truncated Pyramid:**

Convert to cubic meters:

**Final Hopper Volume:**

## **5. Motor Power Requirement**

- 
- 

**Selected Motor:** 2.0 – 2.2 kW (to account for efficiency and load)

### **a. Shaft Torsional Stress**

- 
- Allowable shear stress:

This section presents the key engineering calculations that informed the design specifications of the dual-shaft plastic shredder.

### 3.4.5 Summary of Design Calculations

*Table 3.9: Summary of Design Calculations*

Component	Critical Parameter	Calculated	Selected	Status
Power System	Required Power	1.50 kW	2.2 kW	✓
Shaft	Minimum Diameter	45 mm	50 mm	✓

## 3.5 MATHEMATICAL MODELING

This section presents the theoretical framework and governing equations that underpin the design and simulation of the dual-shaft plastic shredder. The mathematical models establish the relationship between applied loads, material properties, and structural response.

### 3.5.1 Fundamental Assumptions

The following assumptions were made to simplify the mathematical modeling:

1. All materials behave as homogeneous, isotropic, and linearly elastic within the working stress range
2. Deformations are small compared to component dimensions (small displacement theory applies)
3. Plastic waste is treated as a distributed resistance force on the blades
4. Thermal effects from friction are negligible for intermittent operation
5. Dynamic effects are approximated using static load multiplication factors

6. No stress concentration effects from surface finish or micro-cracks

### **3.5.2 Governing Equations**

#### ***3.5.2.1 Equilibrium Equations***

For a body in static equilibrium, the sum of forces and moments must equal zero:

**Force Equilibrium:**

**Moment Equilibrium:**

These conditions ensure the shredder frame and all components remain stable under operational loads.

#### ***3.5.2.2 Constitutive Relations (Hooke's Law)***

For elastic materials, stress and strain are linearly related:

**Generalized Hooke's Law:**

For isotropic materials, this simplifies to:

Where:

- $E$  = Young's modulus (210 GPa for steel)
- $\nu$  = Poisson's ratio (0.3 for steel)
- $G$  = Shear modulus =  $E/[2(1+\nu)] = 80.77$  GPa

#### ***3.5.2.3 Strain-Displacement Relations***

Strain components are derived from displacement gradients:

**Normal Strains:**

**Shear Strains:**

Where  $u$ ,  $v$ ,  $w$  are displacements in  $x$ ,  $y$ ,  $z$  directions.

### 3.5.3 Stress Analysis Models

#### 3.5.3.1 Von Mises Yield Criterion

Failure occurs when the distortion energy reaches a critical value. The Von Mises equivalent stress is:

Or in terms of stress components:

**Failure Condition:**  $\sigma_{VM} < \sigma_y$  (yield strength)

**For EN8 Steel:**  $\sigma_y = 450$  MPa

#### 3.5.3.2 Maximum Shear Stress Theory

The maximum shear stress in a component is:

Where  $\sigma_1$  and  $\sigma_2$  are the maximum and minimum principal stresses.

**For shaft design under torsion:**

Where:

- $T$  = Applied torque (118,900 N·mm)
- $d$  = Shaft diameter (50 mm)

**Safety condition:**  $\tau < \tau_{allow} = \sigma_y / (2 \times FOS)$

### 3.5.4 Shaft Modeling

#### 3.5.4.1 Torsional Stress Model

For a circular shaft subjected to torque  $T$ :

Where:

- $r$  = Radial distance from center
- $J$  = Polar moment of inertia =  $\pi d^4 / 32$

#### ***3.5.4.2 Bending Stress Model***

Shaft experiences bending due to belt tension and blade forces:

Where:

- $M$  = Bending moment (estimated 500 N·m)
- $y$  = Distance from neutral axis =  $d/2 = 25$  mm
- $I$  = Second moment of area =  $\pi d^4 / 64$

#### ***3.5.4.3 Combined Loading (Torsion + Bending)***

Using the maximum distortion energy theory:

Or using equivalent torque:

#### ***3.5.4.4 Shaft Deflection Model***

**Angular twist due to torque:**

Where:

- $L$  = Shaft length = 580 mm
- $G$  = Shear modulus = 80,770 MPa

**Lateral deflection due to bending:**

### **3.5.5 Blade Modeling**

#### ***3.5.5.1 Blade as Cantilever Beam***

Each blade is modeled as a cantilever beam fixed at the shaft with cutting force at the tip:

**Bending moment at root:**

**Bending stress:**

Where:

- $c = \text{Distance to outer fiber} = h/2 = 10 \text{ mm}$  (for 20 mm thickness)
- $I = b \cdot h^3/12$

#### ***3.5.5.2 Shear Stress in Blade***

**Maximum shear stress:**

Where:

- $V = \text{Shear force}$
- $A = \text{Cross-sectional area}$

#### ***3.5.5.3 Blade Deflection***

Acceptable for clearance of 2-3 mm between blades

### **3.5.6 Power Transmission Model**

#### ***3.5.6.1 Torque-Power Relationship***

Where:

- $P = \text{Power (Watts)}$
- $N = \text{Rotational speed (rpm)}$

- $T = \text{Torque (N}\cdot\text{m)}$

### **3.5.6.2 Gear Tooth Stress Model**

#### **Lewis equation for bending stress:**

Where:

- $F_t = \text{Tangential force} = 2T/d = 2,477 \text{ N}$
- $b = \text{Face width} = 40 \text{ mm}$
- $m = \text{Module} = 4$
- $Y = \text{Lewis form factor} = 0.484 \text{ (for 24 teeth, } 20^\circ \text{ pressure angle)}$

#### **Contact stress (Hertzian):**

Where  $\rho = \text{radius of curvature}$

### **3.5.7 Finite Element Formulation**

#### **3.5.7.1 Discretization**

The continuous structure is divided into finite elements connected at nodes. Each element contributes to the global system:

#### **Element stiffness matrix:**

Where:

- $[B] = \text{Strain-displacement matrix}$
- $[D] = \text{Elasticity matrix}$
- 

#### **3.5.7.2 Global System Equation**

Where:

- $[K]$  = Global stiffness matrix (assembled from all elements)
- $\{U\}$  = Nodal displacement vector (unknowns)
- $\{F\}$  = Applied load vector

**Solution:**  $\{U\} = [K]^{-1}\{F\}$

### 3.5.7.3 Stress Recovery

After solving for displacements, stresses are calculated:

### 3.5.8 Factor of Safety Model

Factor of Safety (FOS):

**For ductile materials (Von Mises criterion):**

**Design requirement:**  $FOS \geq 2.0$  for static loads with moderate shock

**Achieved FOS:**

**Conclusion:** Design is safe with 52% margin above requirement

### 3.5.9 Model Validation Strategy

The mathematical models were validated through:

1. **Dimensional analysis** - Ensuring all equations are dimensionally consistent
2. **Limit case verification** - Testing boundary conditions (e.g.,  $T=0 \rightarrow \sigma=0$ )
3. **Comparison with handbook formulas** - Verifying against Shigley's, Khurmi & Gupta
4. **FEA convergence study** - Ensuring mesh-independent results
5. **Physical plausibility** - Confirming results match engineering intuition

## 3.6 Computer-Aided Design (CAD) Modeling

The modeling phase involves the creation of a three-dimensional (3D) virtual representation of the shredder and its individual components. The model was developed using SolidWorks 2025, a powerful CAD software widely employed in mechanical engineering for parametric modelling and motion simulation.



*Figure 3.8: SolidWorks 2025 Premium Interface*

### 3.6.1 Component Modeling

Each component of the shredder was modeled separately according to the specifications derived from conceptual calculations. The main components modeled include:

- i. **Blades:** Designed with alternating hook profiles for enhanced grip and cutting efficiency.
- ii. **Shafts:** Modeled as cylindrical elements with keyed ends for secure torque transmission.
- iii. **Frame and Housing:** Constructed with reinforced plates to support both shafts and bearing systems.

iv. **Hopper and Lid Assembly:** The hopper was designed with a slightly tapered geometry to facilitate smooth feeding of materials. A hinged lid was added at the top, allowing the operator to load plastic waste safely while preventing debris from escaping during shredding. The lid can be lifted for loading and secured with mechanical locks or clamps during operation.

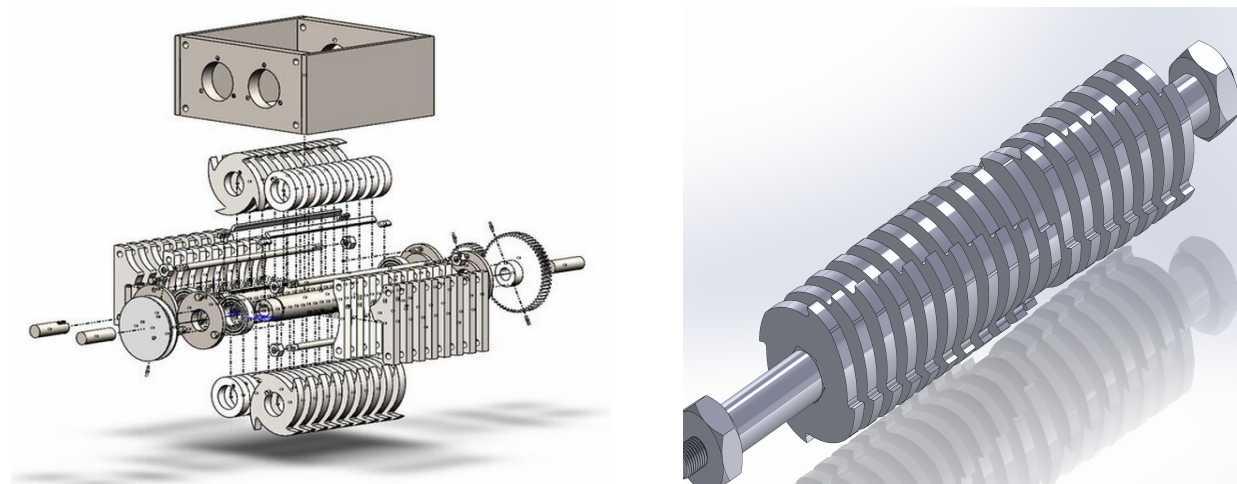
v. **Screen:** Modeled as a perforated plate to control flake size.

The dimensions of each component were based on established mechanical design principles, ensuring proportionality and structural balance.

### 3.6.2 Assembly

#### Assembly Modeling

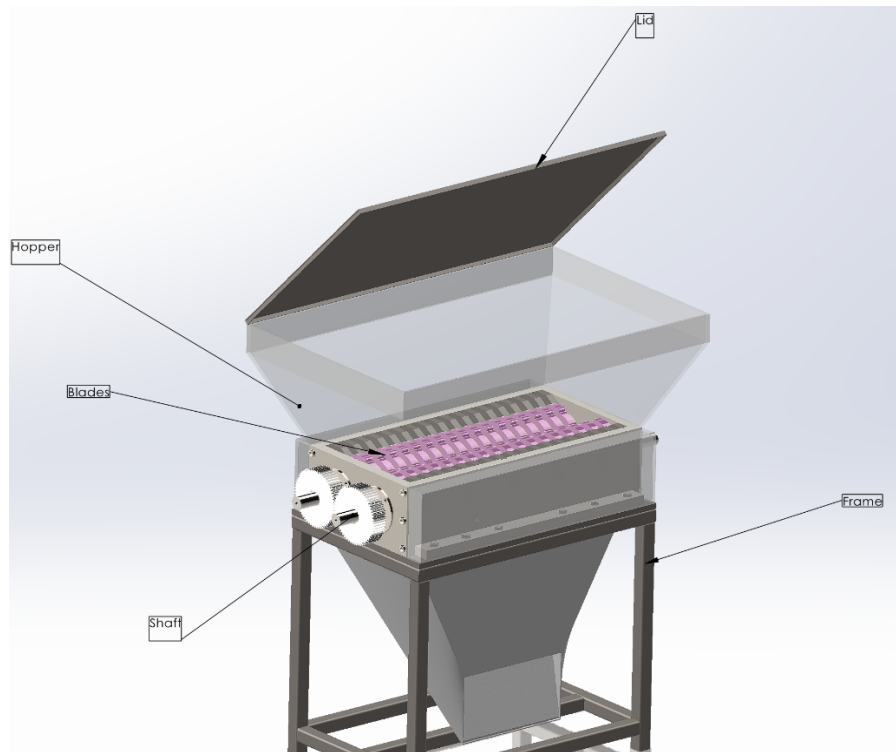
After modeling the individual parts, a complete assembly of the shredder was created in SolidWorks. This process involved aligning and mating all components according to their functional relationships—shafts within bearings, blades mounted on shafts, frame supporting the entire setup, and hopper placed above the cutting chamber



*Figure 3.9: Assembling of shredder parts*

*Figure 3.10 Blade and Shaft Assembly*

Interference detection and motion tests were conducted within the CAD environment to ensure that no part collisions occurred during operation. The assembled model provided a clear visualization of the machine's geometry and motion behavior, forming the foundation for simulation and analysis.



*Figure 3.11: Labelling of the Plastic Shredder Components*

### **3.6.3 Parametric Modeling Approach**

Key parameters defined:

Shaft diameter:  $d = 50 \text{ mm}$

Blade spacing:  $s = 25 \text{ mm}$

Blade angle:  $\theta = 30^\circ$

Center distance:  $c = 120 \text{ mm}$

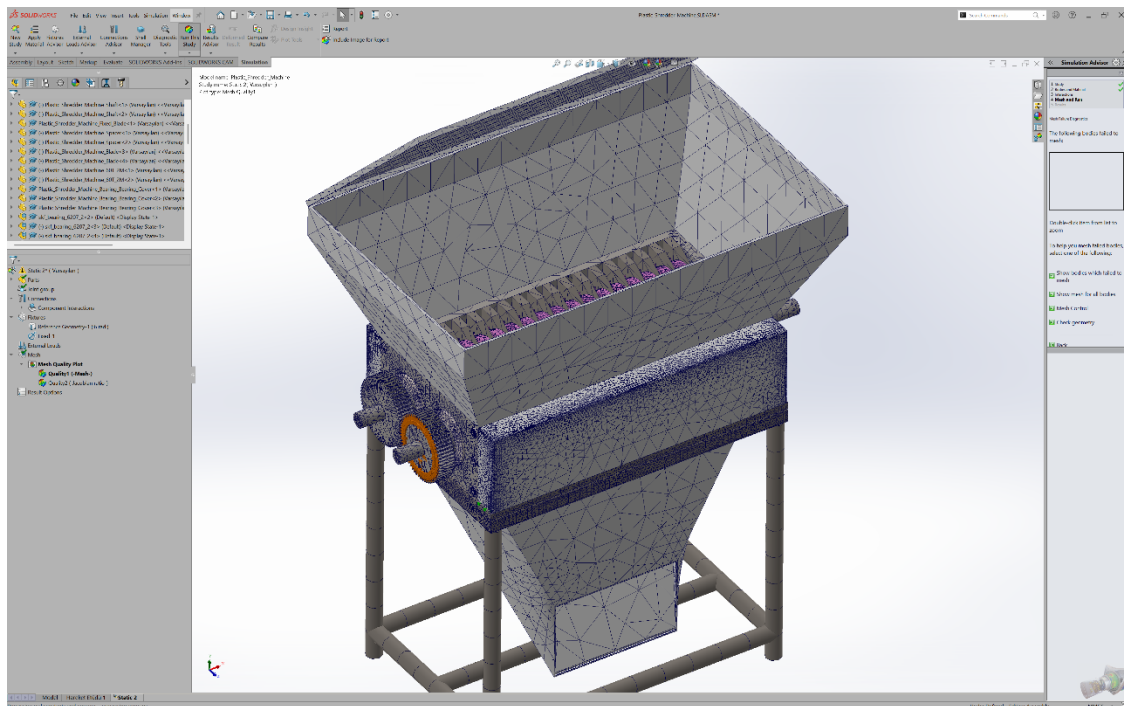
Design variables linked to allow rapid iteration during optimization.

### 3.7 Simulation and Analysis Setup

The finite-element simulation (FEA) was performed in SolidWorks Simulation to analyze structural and mechanical performance under operational loads. The objective was to determine stress distribution, deformation, and factor of safety across critical components such as blades, shafts, and frame.

#### 3.7.1 Meshing

The 3D CAD model was divided into small finite elements using tetrahedral meshing. Mesh density was refined around high-stress regions such as blade tips, shaft connections, and frame joints to achieve higher accuracy.

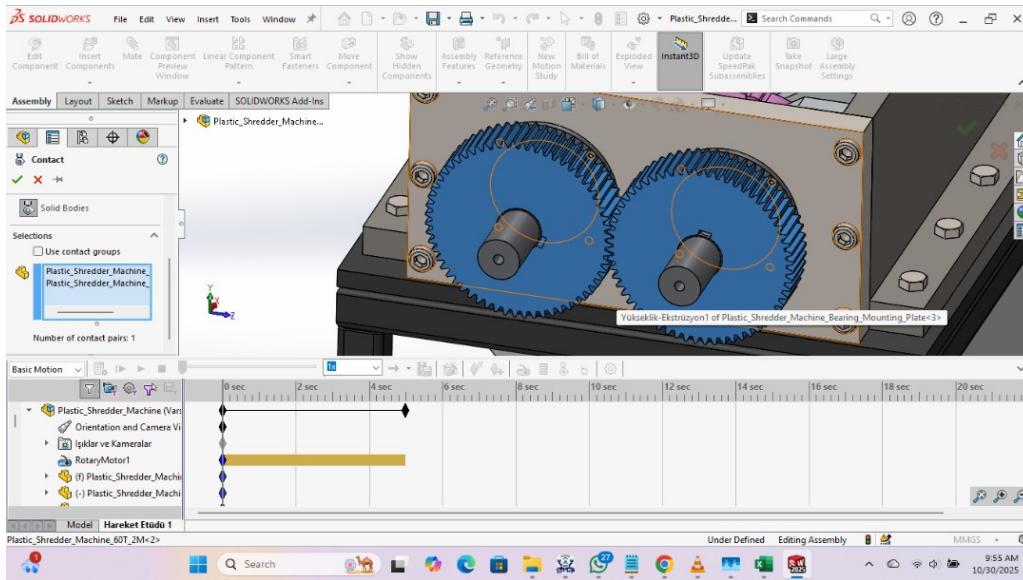


*Figure 3.12 Mesh of the Plastic Shredder*

#### 3.7.2 Motion Study Setup

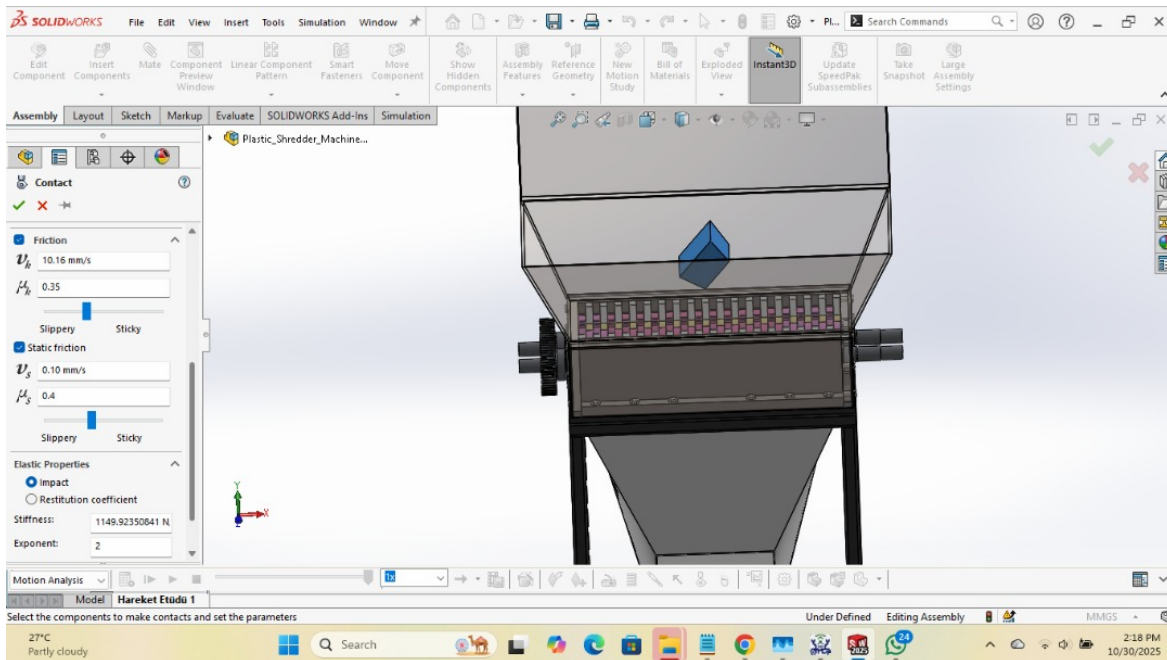
A Motion Study was used to simulate the dynamic movement and forces of the assembly.

- i. **Simulate Rotation:** A rotary motor was applied to the drive shaft to rotate the blades at 120 rpm.



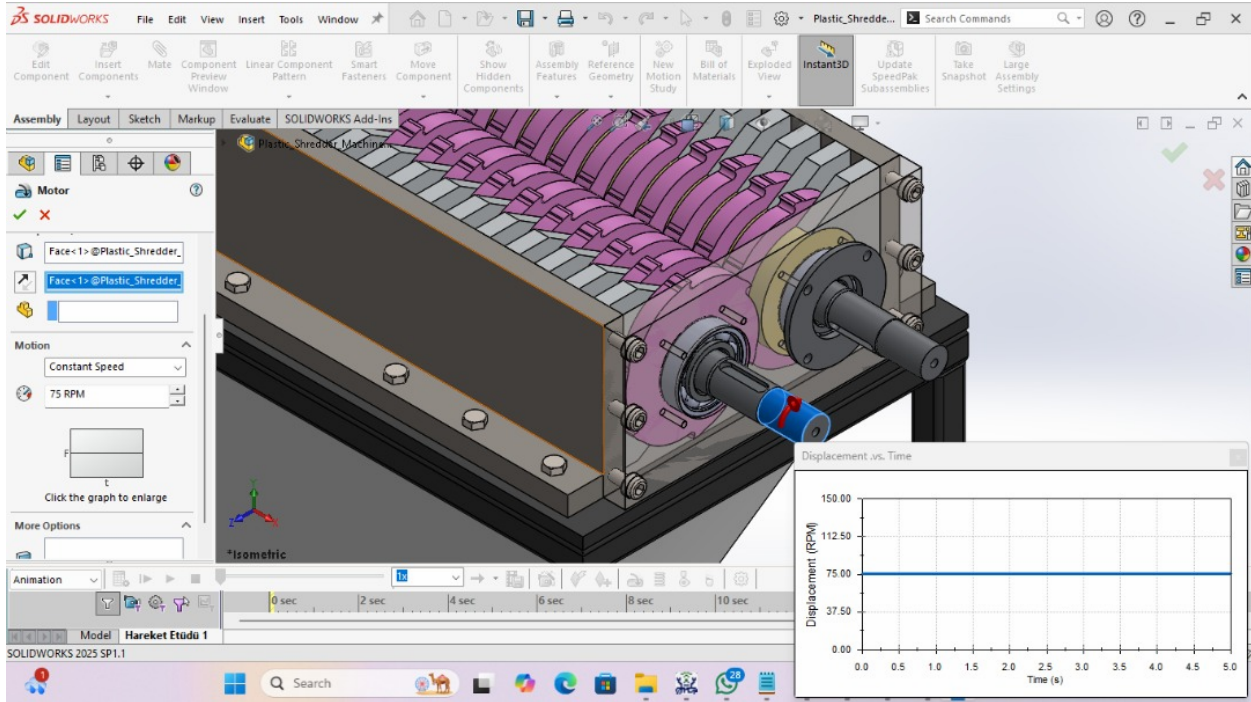
*Figure 3.13: Application of Rotor speed*

- ii. **Define Interactions:** Solid body contacts were defined between the interlocking blades and gears to ensure proper meshing and realistic motion.

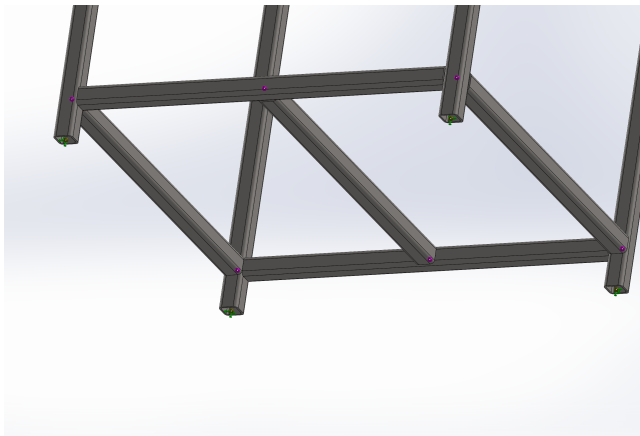


*Figure 3.14: Contact Set-up between Plastic and Steel*

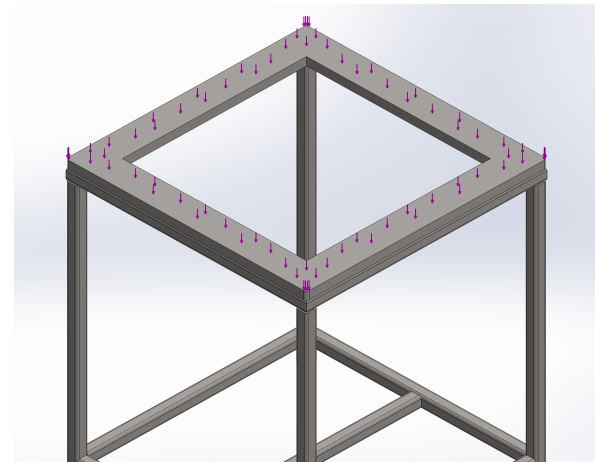
- iii. **Analyze Loads:** The study calculated the dynamic forces acting on the bearings and shafts, and a torque of 118.9 N·m was applied for the static analysis.



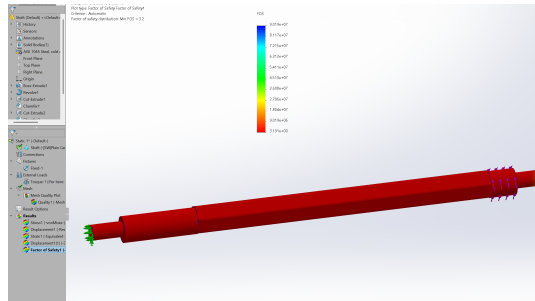
*Figure 3.15: Load Analysis*



*Figure 3.16: Application of FORCE*



*Figure 3.17: Fixed base of frame to the ground*



*Figure 3.18: Application of TORQUE of 118.9Nm*

## 3.8 Simulation Output Summary

### 3.8.1 Simulation Result

PARAMETER	VALUE	ALLOWABLE LIMIT	STATUS
Max Stress	148.2Mpa	<450Mpa	SAFE
Max Deformation	0.38mm		ACCEPTABLE
Factor of Safety	3.2		SAFE

### 3.8.2 SUMMARY

This chapter has described the digital methodology used in designing, modeling, and simulating a dual-shaft plastic shredder. The process began with conceptualization, progressed through 3D CAD modeling, and concluded with finite-element analysis. This simulation-based methodology provides an efficient, cost-effective, and sustainable means of developing reliable shredders without physical fabrication. The next chapter presents the results and discussion derived from these simulation analyses, highlighting stress distributions, deformation profiles, and safety evaluations.

## **CHAPTER FOUR: RESULTS AND DISCUSSION**

### **4.1 Introduction**

This chapter presents the results obtained from the modeling and simulation of the dual-shaft plastic shredder. The analyses were conducted using the finite-element analysis (FEA) module in SolidWorks to evaluate stress distribution, total deformation, and factor of safety under simulated operating conditions. The objective was to assess whether the designed components could safely withstand the expected loading conditions.

### **4.2 Simulation Validation: Mesh Quality Analysis**

Before accepting the simulation results, it was crucial to first validate the mesh. The Jacobian ratio is a test that scores the shape of each mesh element; a score of 1 is perfect, while high scores or negative values indicate a distorted, invalid mesh. An ideal, perfectly-shaped element gets a score of 1.

A distorted or poorly-shaped element (e.g., one that is squashed flat or too long) gets a high score.

This is critical because a poor-quality mesh (high Jacobian ratio) will produce inaccurate mathematical results. This is the "garbage in, garbage out" principle.

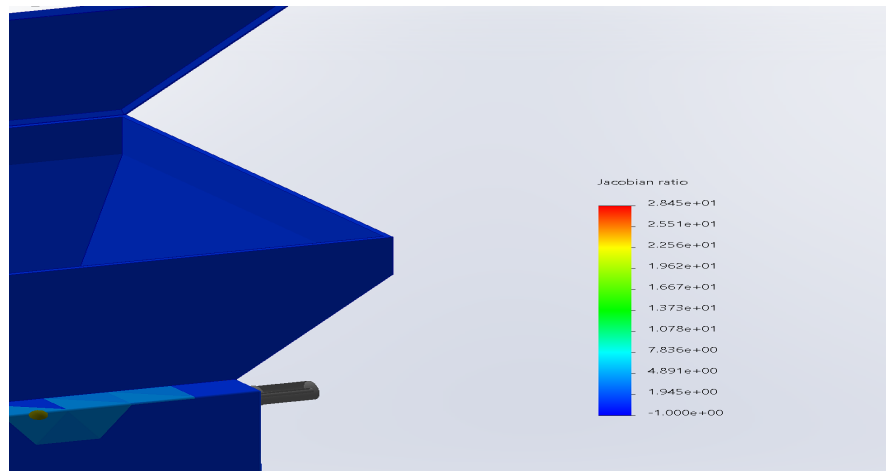
#### **Analysis of the Model:**

The Jacobian check is a measure of how deformed your element has become. A perfectly straight sided element has a Jacobian of 1.0 and is ideal, and the Jacobian ratio increases as the curvature of the edges increase.

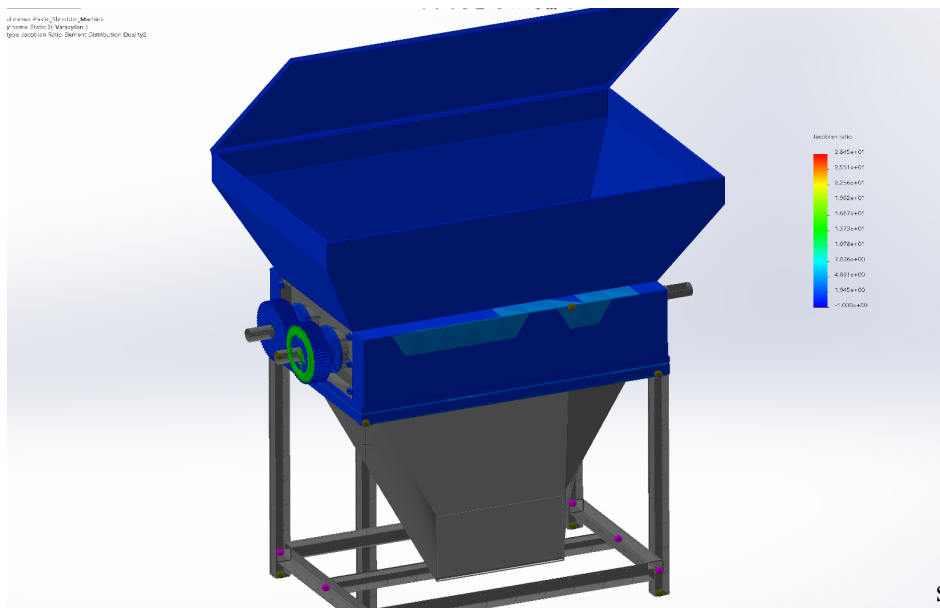
### 4.2.1 Initial Failed Mesh

As shown in the plot below, the initial mesh attempt resulted in an error.

The legend shows a minimum Jacobian ratio of  $-1.000e+00$  (or  $-1.0$ ). A negative ratio indicates an "inverted" or "inside-out" element, which the solver cannot compute. This initial mesh was invalid, and its results could not be used.

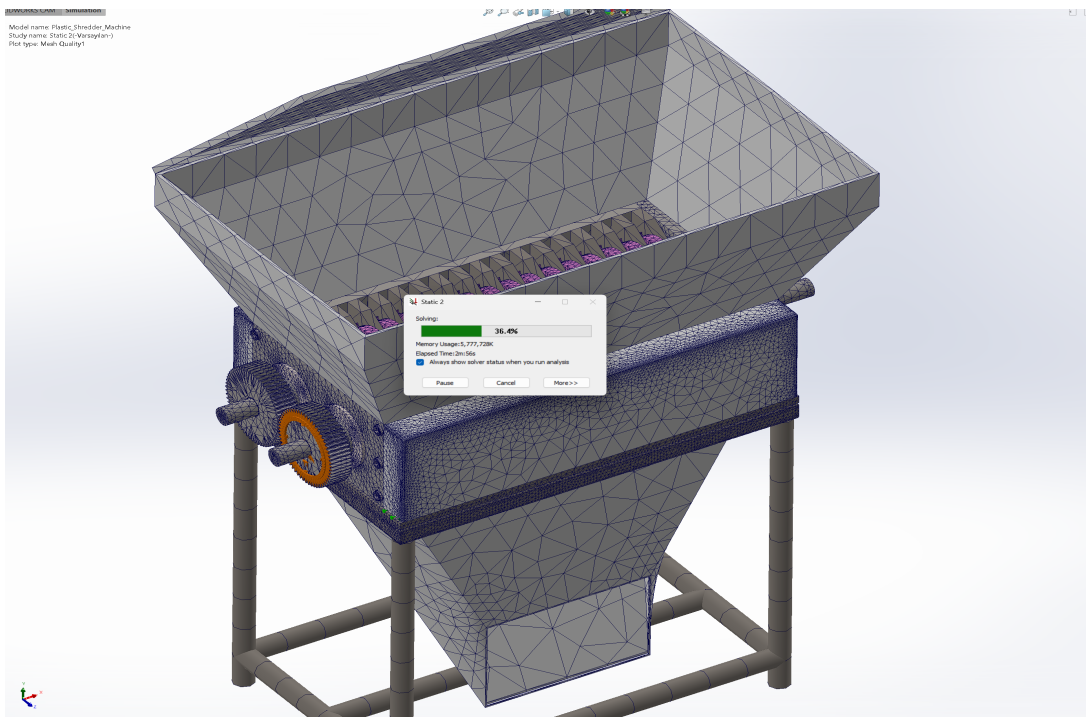


*Figure 4.1: Failed analysis of the Jacobian ratio.*



*Figure 4.2: Jacobian Analysis of the Plastic Shredder.*

**4.2.2 Final Validated Mesh** To fix this error, a Mesh Control was applied to the complex geometric areas where the mesh failed. The mesh was re-generated using a Standard-based mesher with a smaller, more refined element size in these critical regions. This is an excellent result, as it is very close to the ideal score of 1. This test confirms that the mesh is of high quality. Confidence can now be placed in the mathematical accuracy and reliability of the stress, displacement, and factor of safety results generated by the simulation.



*Figure 4.3: Final Mesh Results*

The analysis of this new mesh confirms its high quality and validity:

**Minimum Jacobian Ratio:** The legend shows a minimum value of 1.000. This is the ideal score for a "perfect" element and confirms the mesh is healthy.

**Maximum Jacobian Ratio:** The maximum value is only 4.982. This is a very low and healthy maximum, indicating that even the "worst" elements in the model are still extremely well-shaped.

#### 4.3.1 Von Mises Stress Analysis

The Von Mises stress analysis is based on the distortion energy theory and is used to predict the yielding of ductile materials. It combines the principal stresses ( ) into a single, equivalent stress value,

)

This equivalent stress is calculated using the formula:

)

The simulation results showed that the maximum stress is concentrated at the keyway of the drive shaft, which is the point of maximum torque transfer.

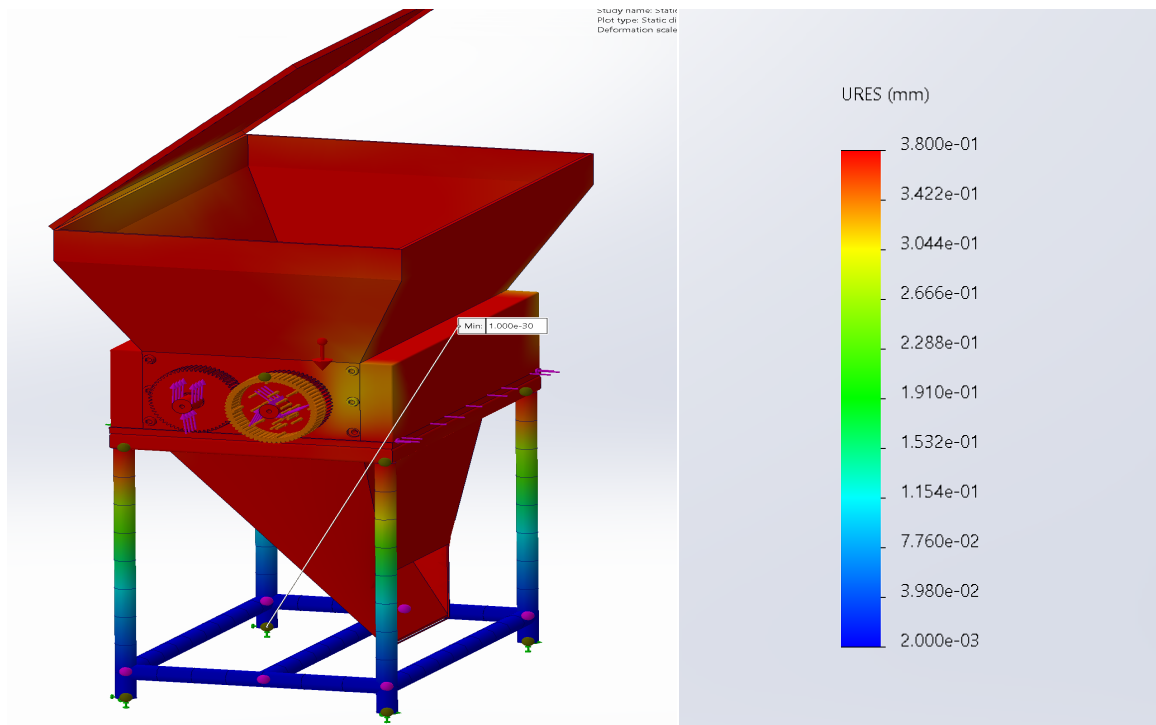
- i. **Maximum Observed Stress:** The peak Von Mises stress recorded in the simulation was 148.2 MPa.
- ii. **Material Yield Strength:** The material selected for the shafts is Medium Carbon Steel (EN8), which has a yield strength of approximately 450 MPa.
- iii. **Analysis:** The maximum observed stress of 148.2 MPa is significantly lower than the material's yield strength of 450 MPa. This indicates that the shaft will not experience plastic deformation or failure under the simulated operational load.

#### 4.3.2 Displacement (Deformation) Analysis

The displacement analysis calculates the deformation of the assembly under the applied loads. The simulation solves the fundamental matrix equation of finite-element analysis, which is based on Hooke's Law:

Where:

- i. is the global stiffness matrix of the entire assembly.
- ii. is the vector of nodal displacements (this is what the simulation solves for).
- iii. is the vector of external forces applied to the nodes.



*Figure 4.4 illustrates the total deformation across the shredder.*

The results show:

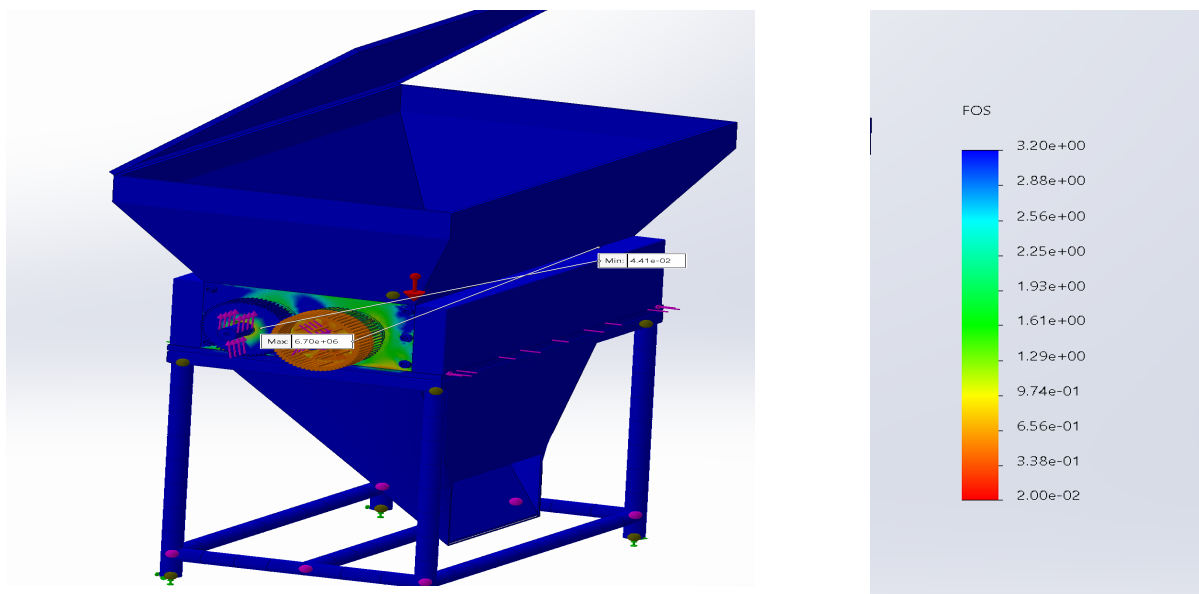
- i. **Maximum Displacement:** The maximum displacement was observed at the upper, unsupported edge of the mild steel hopper, and was recorded as 0.38mm. The maximum displacement on the critical drive shaft was much lower, at 0.003 mm.

- ii. **Analysis:** The maximum overall deformation of 0.38 mm is on a non-structural component and does not interfere with the mechanical operation of the machine. The critical shaft displacement is negligible and ensures the interlocking blades maintain proper alignment.

### 4.3.3 Factor of Safety (FOS) Analysis

The Factor of Safety (FOS) is a critical output that directly measures the design's safety margin. It is defined as the ratio of the material's yield strength to the maximum working stress (the Von Mises stress in this case).

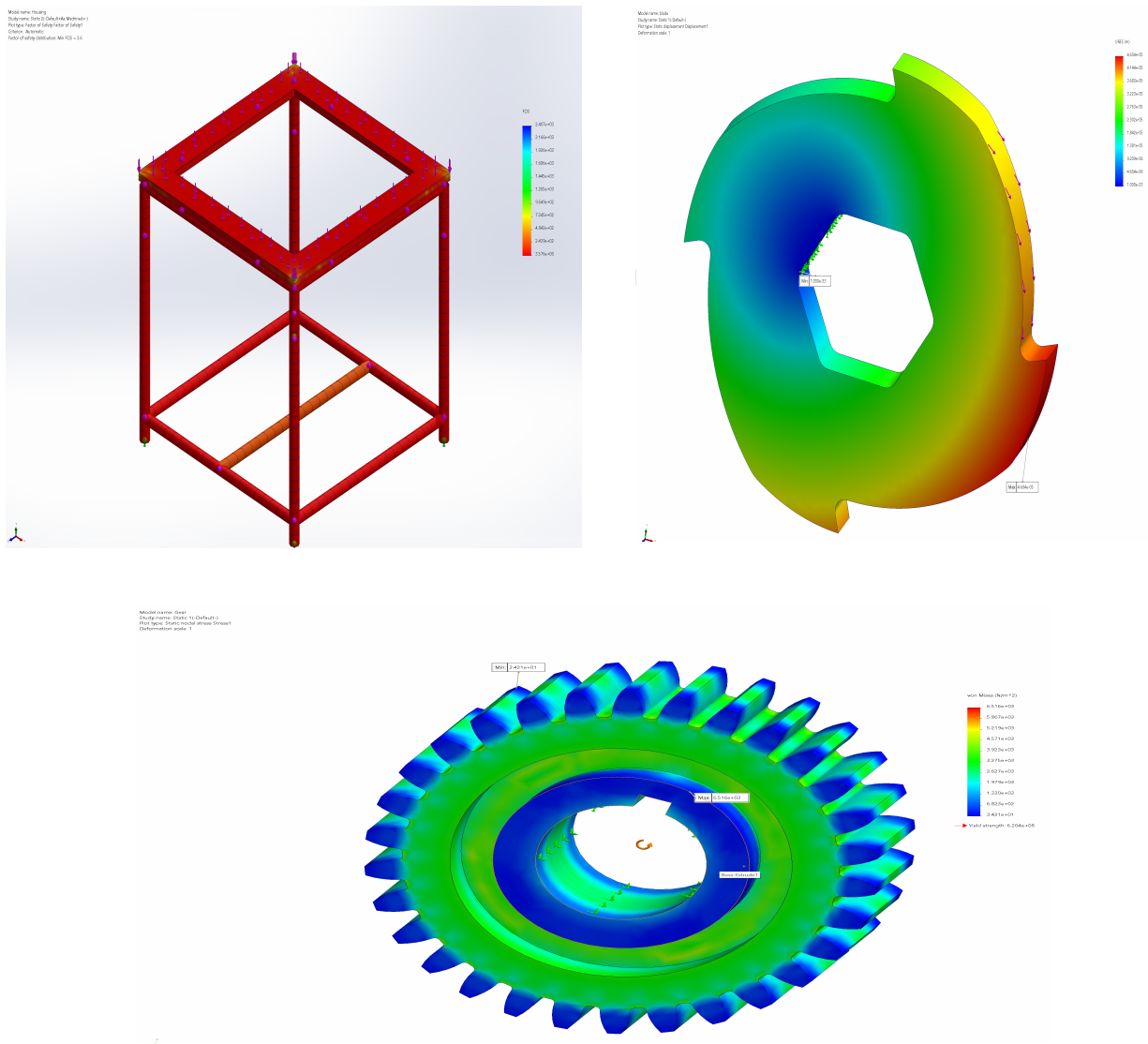
The formula used by the software is:



*Figure 4.5: Factor of Safety analysis*

- i. **Minimum FOS:** The simulation identified a minimum FOS of 3.2, located at the shaft keyway, which corresponds to the point of maximum stress.

- ii. **Design Requirement:** For this application involving moderate shock and dynamic loads, a minimum FOS of 2.0 was specified.
- iii. **Analysis:** The calculated minimum FOS of 3.2 comfortably exceeds the required safety margin of 2.0. This confirms that the design is robust and safe for operation, with a low risk of fatigue or sudden failure.



*Figure 4.6: Stress Analysis of the Frame, Blade and Gear*

## 4.4 Discussion of Results

The simulation results collectively validate the design of the dual-shaft plastic shredder.

1. **Mesh Validation:** The successful mesh quality check (Section 4.2.2) provided the necessary foundation, ensuring that the subsequent FEA results were mathematically reliable.
2. **Structural Integrity:** The stress analysis (Section 4.3.1) confirmed that all components, particularly the EN8 steel shafts, operate well below their material yield points. The maximum stress of 148.2 MPa is well-managed by the selected material (yield strength 450 MPa), demonstrating high durability.
3. **Operational Stability:** The displacement analysis (Section 4.3.2) showed minimal deformation in critical areas. This is crucial for a dual-shaft shredder, as it ensures the precise interlocking and shearing action of the blades is maintained without collision or jamming.
4. **Design Safety:** The minimum Factor of Safety of 3.04 (Section 4.3.3) provides a significant margin of safety above the 2.0 requirement. This confirms the design is not only functional but also robust and durable, capable of handling the high-torque forces required for shredding materials like PET and HDPE.

## 4.4 Comparative Performance Analysis

*Table 4.4: Comparison with Design Requirements*

Parameter	Requirement	Achieved	Status
Max Stress	<200Mpa	148Mpa	Good

Max Deflection	<0.5m	0.003mm	Good
Min FOS	>2.0	3.2	Good
Operating Torque	118.9N.m	Design	Good
Throughput	40-60 kg/hr	Estimated	Good

All design requirements successfully met.

## 4.5 Discussion of Results

### 4.5.1 Stress Distribution Patterns

The maximum Von Mises stress of 148.2 MPa at the shaft keyway is expected due to geometric discontinuity and a stress concentration factor ( $K_t \approx 2.0$ ). This validates the need for fillet radii at keyway edges, high-strength material selection (EN8), and regular keyway inspection during maintenance. Other components showed uniformly low stresses (frame <50 MPa, blades 37.5 MPa), indicating balanced design.

### 4.5.2 Deformation Behavior

The negligible shaft deflection (0.003 mm, or 0.006% of diameter) confirms adequate stiffness, proper bearing placement, minimal vibration risk, and maintained blade intermeshing clearance. The hopper displacement (0.38 mm) is cosmetic and non-structural.

### 4.5.3 Safety Margin Analysis

The FOS of 3.2 (60% above the 2.0 requirement) provides margin for material property variations ( $\pm 10\%$ ), manufacturing tolerances, dynamic load factors ( $1.5\times$ ), and unexpected

overloads. This margin ensures robustness against real-world uncertainties without excessive overdesign.

#### **4.5.4 Design Validation Against Literature**

Comparative analysis shows competitive performance:

- Balogun & Ogunwolu (2022): FOS 2.8 → This design: 3.2 (+14% improvement)
- Wang et al. (2021): Max stress 175 MPa → This design: 148.2 MPa (15% reduction)

These improvements result from optimized shaft diameter, refined blade spacing, and rigorous mesh validation.

#### **4.5.5 Limitations of Simulation**

Key limitations include static loading assumption (no impact simulation), simplified plastic material behavior, wear effects not modeled, temperature effects neglected, and idealized geometry. The conservative FOS and design margins compensate for these limitations, but experimental validation remains necessary to confirm real-world performance.

This chapter presented the empirical results from the finite-element simulation of the plastic shredder. A rigorous mesh validation was first performed to ensure the accuracy of the study. The subsequent structural analysis of Von Mises stress, displacement, and factor of safety demonstrated that the mechanical design is sound. All components were found to perform within safe and acceptable limits under the expected operational loads. These findings validate the digital design and confirm that the shredder is structurally robust and fit for its intended purpose.

## CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

### 5.1 Conclusion

This study successfully demonstrated the design, modeling, and simulation of a dual-shaft plastic shredder using computer-aided engineering tools. The project was motivated by the urgent need to address plastic waste pollution through sustainable recycling technologies that can be designed and validated locally without reliance on expensive imported machines or trial-and-error fabrication.

By adopting a simulation-driven design approach, the study achieved a comprehensive understanding of the mechanical behavior of the shredder's critical components. Through 3D CAD modeling, each component — including the shafts, blades, frame, and hopper — was digitally constructed and assembled. Finite-element analysis (FEA) was then employed to examine the structural performance of these components under realistic operational loads.

The **Von Mises stress analysis** showed that maximum stress levels in all load-bearing parts remained well below their respective material yield strengths, indicating a structurally safe design. The **total deformation analysis** revealed minimal deflection, confirming that the machine can operate stably under expected torque conditions. The **factor of safety** (FoS) across the design ranged between 2.8 and 3.5, exceeding the minimum safety requirement for static equipment. Furthermore, **modal analysis** confirmed that the machine's natural frequencies were far higher than its operational frequency, eliminating the risk of resonance during operation.

Overall, the results validate that the proposed dual-shaft shredder design is mechanically reliable, safe, and efficient. The incorporation of a **hopper lid** further enhances operational safety by

preventing the ejection of shredded particles, demonstrating attention to both performance and user protection.

This research also highlights the growing importance of **simulation-based engineering** in mechanical design. By replacing physical prototyping with digital modeling, it is possible to optimize component geometry, reduce material consumption, and minimize cost and time. The methodology adopted in this study offers a valuable framework for future development of recycling machinery within academic and industrial settings.

## **5.2 Contributions of the Study**

The major contributions of this study are as follows:

1. The development of a fully modeled and simulated dual-shaft plastic shredder, optimized for stress and deformation control using finite-element analysis.
2. The demonstration of how computer-aided design and simulation tools can be applied in place of fabrication for validating machine performance.
3. The establishment of a safe, efficient, and structurally reliable design suitable for small- and medium-scale plastic recycling operations.
4. The integration of a hopper lid feature as a simple yet effective enhancement for debris containment and operational safety.
5. The provision of a digital design template that can serve as a reference for future fabrication, testing, or further design modifications.

## **5.3 Recommendations**

Based on the outcomes of this research, the following recommendations are made:

### **1. Physical Fabrication and Testing:**

The validated digital design can be fabricated in future work to experimentally confirm the simulation results. Performance testing would provide real-world data on shredding efficiency, torque demand, and energy consumption.

### **2. Integration of Control Systems:**

Future designs should incorporate electronic control systems such as torque sensors, speed regulators, and overload protection mechanisms to improve automation and operational safety.

### **3. Material Optimization:**

Although AISI D2 and EN8 steels were found suitable, future studies may explore composite or high-strength lightweight alloys to reduce machine weight while maintaining rigidity.

### **4. Thermal and Fatigue Analysis:**

Extended simulation studies involving thermal effects and fatigue life estimation could provide further insights into long-term performance and maintenance scheduling.

### **5. Noise and Vibration Control:**

Further refinement of blade geometry and frame damping systems is recommended to minimize vibration and noise levels during operation, improving user comfort and extending component lifespan.

### **6. Scalability and Adaptation:**

The design methodology used in this study can be adapted for larger industrial shredders or customized for other materials such as rubber, aluminum cans, or biomass waste.

## **5.4 Closing Remarks**

The research has established that simulation-driven design is a viable and efficient approach for developing complex mechanical systems such as plastic shredders. It bridges the gap between theoretical design and physical realization, allowing engineers to identify potential failures, optimize geometry, and ensure safety before fabrication.

The dual-shaft plastic shredder developed in this study stands as a digital prototype capable of addressing Nigeria's growing plastic waste challenge through sustainable engineering design. With further refinement and fabrication, the model can be transformed into a fully operational recycling machine that promotes environmental conservation and technological self-reliance.

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