JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF GRADUATE STUDIES

FACULTY OF MECHANICAL ENGINEERING

FINITE ELEMENT ANALYSIS, AND DESIGN OPTIMIZATION OF SINGLE SHAFT TRIPLE JAW PLASTIC SHREDDER ROTOR

BY: EDOSA KEFYALEW

A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF JIMMA UNIVERSITY FOR PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER'S OF SCIENCE IN DESIGN OF MECHANICAL SYSTEMS

OCTOBER, 2021
JIMMA, ETHIOPIA

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ADVISOR: PROF. ***HIRPA G. LEMU (PH.D.)***

CO-ADVISOR: ***DR. JOHNSON SANTHOSH (PH.D.)***

OCTOBER, 2021
JIMMA, ETHIOPIA

DECLARATION

I, the undersigned, declare that this thesis entitled "*Conceptual Design, Finite Element Analysis [FEA] and Optimization of Single Shaft Triple Jaw Plastic Shredder Rotor*" is my original work, and has not been presented by any other person for an award of a degree in this or any other university.

Researcher: *Mr. Edosa Kefyalew* (Assistant Lecturer in Mizan-Tepi University)

Signature: ______________________________ Date: ____________________

APPROVAL

As a member of the examining board of open defense, we have checked and evaluated the Master's Thesis prepared and presented by *Edosa Kefyalew Tesema* entitled **"Finite Element Analysis (FEA) and Design Optimization of Single Shaft Triple Jaw Plastic Shredding Machine Rotor"** Hereby we certify this work fulfilled the requirement of the Degree of Masters of Science in Mechanical Engineering (Design of Mechanical System).

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This thesis is dedicated to my father (Abba Lenca: Kefyalew Tesema Tuji) whom I lost in the course of this master's program.

Abbaa Kiiyya: "Boolla kee bookni haa guutu,

abjuun kee naan haa guutu"

ABSTRACT

Plastic waste causes serious environmental pollution and exhaustion of landfill space. One of the main reasons for this plastic-based waste is the lack of a full recycling process. In the recycling process shredding is one of the crucial stages where the main size reduction takes place. The size reduction in single shaft shredder is done by shearing and/or crushing the plastic between stationary blades that are bolted on to the casing and rotating blades mounted on the rotor. In this thesis work the effort is taken on finite element analysis, and design optimization of shredder rotor.

In the conceptual design, three concept variants, namely flat arrangement, scissor arrangement, and staggered arrangement were considered and evaluated by assigning performance criteria. According to the considered criteria, their weighting percentages were found to be 65.42%, 64.42%, and 66.75% respectively. As a result, due to the higher weighting the staggered arrangement is selected as an appropriate concept for further analysis.

In the same manner for attaching the shaft with the blade carriage three different types of shafts, namely, cylindrical, hexagonal, and splined shaft were considered and analyzed on ANSYS®V19R1. The static structural analysis is conducted on three of them with the same loading and boundary conditions. Accordingly, the maximum deformation result are 0.040 mm, 0.003 mm, and 0.028 mm whereas, the equivalent Von-Mises stress for cylindrical, hexagonal, and splined shaft are 216.92 MPa, 45.483 MPa, and 45.478 MPa respectively. As the splined shaft coupled with the blade carriage has lower deformation and stress. Thus, it is considered as the best mechanism.

The topology optimization of blade carriage after smoothing resulted with 17.5% mass reduction. For the parametric optimization of blade carriage of the rotor, five input and three output parameters were considered to parametrically optimize the blade carriage. From Design Exploration response surface, response surface optimization, were conducted. The parametric optimization, which was conducted on the blade carriage resulted in three candidate parameters from which the best candidate is used with little approximation to remodel the blade carriage. The optimized parameters of the carriage are P_1=9mm, P_2 = 52.5 mm, P_4 = 31 mm, P_5 = 51 mm, P_6 = 162.5 mm.

***Keywords**: Plastic recycling, Shredder rotor, Conceptual design, FEA, Optimization.*

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LIST OF ACRONYMS

ACC: *American Chemistry Council*

AHP *Analytical Hierarchy Process*

AISI: *American Iron and Steel Institute*

AJOL: *African Journal Online*

ANSYS: *Analysis System*

CD-ROM: *Compact Disk- Read Only Memory*

CNC: *Computer Numerical Control*

DOE: *Design of Experiment*

EIPO: *Ethiopian Intellectual Property Office*

ETB: *Ethiopian Birr*

FDM: *Fused Deposition Modeling*

FEA: *Finite Element Analysis*

FUTA: *Federal University of Technology, Akure*

HDPE: *Higher Density Polyethylene*

JIT: *Jimma Institute of Technology*

LDPE: *Low-Density Polyethylene*

LSC: *Local Sensitivity Curves*

MATLAB: *Matrix Laboratory*

MCDM *Multi-Criteria Decision Making*

MOGA: *Multi-Objective Genetic Algorithm*

MSW: *Municipal Solid Waste*

NFRC: *Natural Fiber Reinforced Composite*

NGO: *Non-Governmental Organization*

PE:	*Polyethylene Terephthalate*
PO	*Parametric Optimization*
PP:	*Polypropylene*
PS:	*Polystyrene*
PVC:	*Polyvinyl Chloride*
SAA:	*Styrene Acrylic Acid*
SPI:	*Society of the Plastics Industry*
TO:	*Topology Optimization*
UNEP:	*United Nations Environment Program*
UVR:	*Ultra-Violet Radiation*
WRM	*Weighted Rating Method*

SYMBOLS

x *Number of 1's*

n *Total number of criteria*

A_{sh} *Area under shear*

w *Width of plastic under shear*

t *The thickness of the plastic under shear*

S_{ut} *Ultimate tensile stress*

S_{us} *Permissible tensile stress*

τ *Shear stress*

CHAPTER ONE

1. INTRODUCTION

1.1. BACKGROUND OF THE STUDY

Over the past 50 years, there has been a global increase in the production of plastic, from 2 million metric tons in 1950 to 381 million metric tons in 2015, and is anticipated to double in the next 20 years [1], [2]. The total global production of plastics up to date is estimated at 0.083 billion metric tons [3], with 64 million metric tons produced in Europe alone. China is one of the large producers of plastics in the world, accounting for more than one-quarter of the global production [4]. Implying that as more resources are being used to meet the increased demand for plastic, more plastic waste is being generated [5].

Being a versatile, lightweight, strong, and potentially transparent material, plastics are the drivers for its growth and ideal suitability for a variety of applications. Besides containing liquid, packaging plastic materials are used in medical delivery systems, artificial implants and other healthcare applications, water desalination and removal of bacteria, etc. [6]. According to [4], replacement of plastic in packaging by glass, paper, cardboard, or metals wood lead to drastic increases the weight by (>400%), the cost by (>200%), the volume by (>200%) and the energy consumed by (>200%). This shows the preferability of plastic over other materials.

Almost 75% of the demand for plastic products comes from four major sectors: packaging, construction, automotive and electrical or electronics. The total primary production of plastics consumed by each sector is packaging (163 Mt), building and construction (73 Mt), textiles (67 Mt), consumer and institutional products (47 Mt), transportation (30 Mt), electrical/electronic (20 Mt) and industrial machinery (3Mt). This is the reason why most engineers and manufacturers readily turn to plastics because they offer combinations of properties not available in any other materials. Plastics offer advantages such as bio-inertness, lightness, resilience, resistance to corrosion, colorfastness, transparency, ease of processing, etc., and although they have their limitations, their exploitation is limited only by the ingenuity of the designer [7].

Specially designed plastics have been an integral part of the communication and electronics industry, especially in the manufacture of chips and compartments. They are also used in alternative energy systems such as fuel cells, batteries [8].

Plastic materials, though cheap, available, and serve society's needs, are not very durable compared to metals. They are easily damaged. This means that they constitute a menace to the environment. Pollution of this form is not suitable for a clean and healthy environment. Plastic as a solid waste can take the form of damaged washing bowls, jerry cans, food storage containers, liquid bottles footwear, buckets, plates, seats, etc. the disadvantages caused by the massive use of plastics are invidious. These plastics being synthetic rather than natural are frequently not broken down by microorganisms in the way that natural polymers are [9].

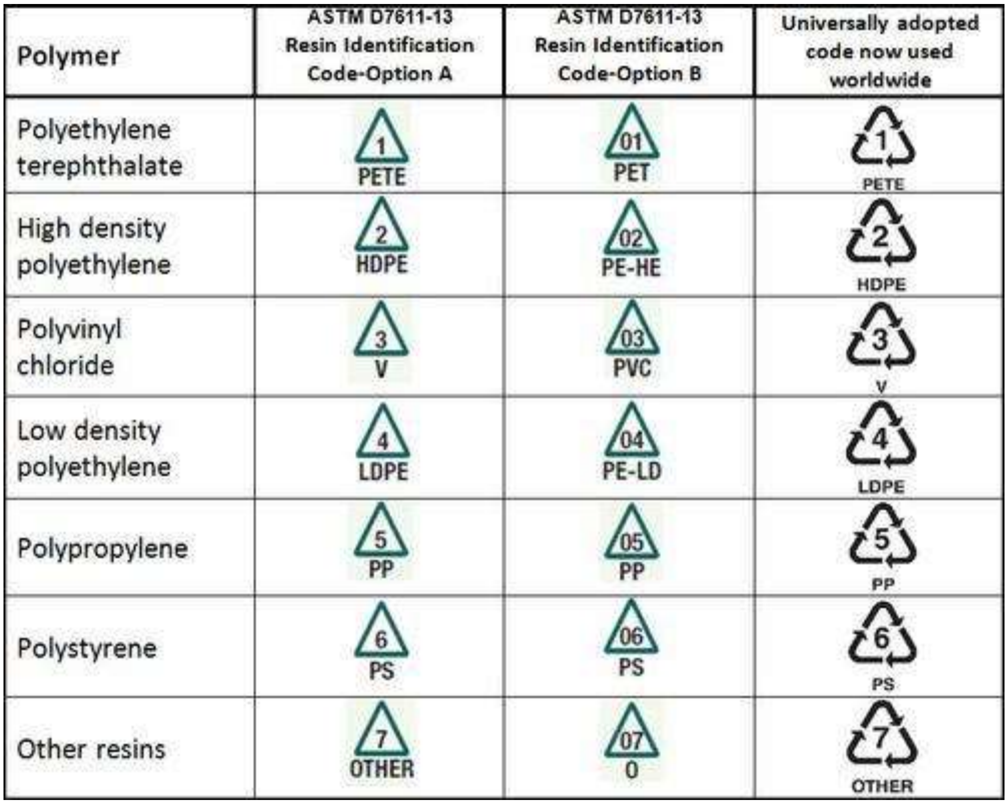
For reducing or eradicating environmental pollution, there are some plastic waste management systems. The waste management process is the collection, transportation, processing and disposal, managing, and monitoring of waste materials. Those systems are different in applications and the degrees of significance they have in the conservation of the ecosystem. Those systems are namely: prevention, minimization, reusing, and recycling.

Prevention: Prevention is the legal banning of the production, transportation, utilization of plastic materials. Worldwide many countries banned the import and manufacture of plastic bags partially or fully [10,11]. Even though prevention can be the best mechanism for the elimination of environmental pollution, however, it is difficult to ban the usage of all types of plastic materials other than plastic bags and packaging.

Minimization: Minimization is reducing the use of goods made from plastic, especially disposable items.

Reuse: is the repeated use of plastic-based items for different purposes.

Recycling: Involves the treatment or reprocessing of a discarded waste material to make it suitable for subsequent re-use either for its original form or for other purposes. Recycling is done by processing plastic waste that does not have economic value through physical or chemical processes or both so that products can be used or sold again [12]. This recycling is carried out by sorting plastic in its coding and color. ***American Society for Testing and Materials (ASTM)*** classifies plastic materials into 7 different categories (Figure 1-1). These are Polyethylene Terephthalate (PET), Higher Density Polyethylene (HDPE), Polyvinyl Chloride (PVC), Low-Density Polyethylene (LDPE), Polypropylene (PP), Polystyrene (PS), and others.



Polymer	ASTM D7611-13 Resin Identification Code-Option A	ASTM D7611-13 Resin Identification Code-Option B	Universally adopted code now used worldwide
Polyethylene terephthalate	1 PETE	01 PET	1 PETE
High density polyethylene	2 HDPE	02 PE-HE	2 HDPE
Polyvinyl chloride	3 V	03 PVC	3 V
Low density polyethylene	4 LDPE	04 PE-LD	4 LDPE
Polypropylene	5 PP	05 PP	5 PP
Polystyrene	6 PS	06 PS	6 PS
Other resins	7 OTHER	07 O	7 OTHER

Figure 1.1: The different coding systems used for plastic recycling [13]

The recycling process can be further categorized into mechanical recycling or feedstock recycling.

Mechanical recycling includes collecting, sorting, shredding/crushing, washing, further grinding and extrusion by heat. Because thermosets cannot be remolded by the effect of heat, this type of recycling is mainly restricted to thermoplastics.

Feedstock recycling is also called chemical or tertiary recycling. It is the decomposition of polymers employing heat, chemical agents, and catalysts [14].

In the mechanical plastic recycling process, shredding is one of the important stages which is mainly used for size reduction by shearing and crushing. Waste plastic shredder is a machine that reduces used plastic bottles to smaller particle sizes to enhance their portability, easiness, and readiness for use into another new product. A shredder can be classified mainly according to the number of working shafts to single-shaft [15], double-shaft [16], and four shafts. They may also be configured according to each unique application, different speed of rotation, power supply, number of cutting blades, shaft diameter, the thickness of spacing collars, power of drive, degree of pressurization, productivity.

1.2. STATEMENT OF THE PROBLEM

In the plastic material recycling, a lot of different types of plastic shredding machines are utilized. They come with different size and rotor arrangement. As the shredder rotor is the main components of plastic shredder it needs thorough design and optimization. This is because the shredding action takes place between the rotating blades (rotor) and the stationary blades. The shredding action takes place by mainly shearing action. Additionally, it may happen by crushing and/or impact load. In a shearing process the surface area under shear can have an effect on the performance of the rotor.

Some problems with existing shredder rotor are the minimum performance due to the increasing of the shear area. The other problem is the lack of detachable design between the shaft and the carriage. On the conceptual design the former design simply selected without comparing concepts and selecting the appropriate one. And also, the optimization of the shredder components are rarely considered.

Therefore, this thesis aims to design, analyze, and optimize single shaft triple jaw plastic shredding machine rotor which facilitates the recycling rate of plastic waste.

1.3. RESEARCH OBJECTIVES

- **General Objective**

The general objective of this research is FEA and design optimization of single shaft triple jaw plastic shredding machine rotor.

- **Specific Objectives**

The specific objectives of this thesis are:

1. To do conceptual design on the shredder rotor
2. Finite element analysis of the components
3. To do topology optimization on the blade carriage
4. To do parametric optimization on the blade carriage

1.4. SCOPE OF THE RESEARCH

The *extent of this work is* conceptual design, modeling of shredder rotor on *SOLID WORKS*®, analysis of rotor on ANSYS®, and optimization of the parts. In the conceptual design, a product development generic process is used. All the parts of the rotor are modeled by *SOLID WORKS*®V19R3. The static structural analysis, the topology optimization, and the parametric optimization are conducted on the ANSYS®V20R1 workbench. The parametric optimization of the blade carriage is conducted with ANSYS design explorer. In the design explorer response surface, response surface optimization and six-sigma analysis are utilized.

1.5. OUTLINE OF THE THESIS

Following this introduction section, which covered the motivation and background, problem statement, objectives of the research, scopes of the research, and research methodology, the thesis is divided into five chapters. Chapter 2 deals with a literature review, where a review of the origin and revolution of plastic materials, plastic value chain, and the plastic waste management systems, as well as the importance of recycling to eliminate plastic pollution and at the end, are conducted and reported.

Chapter three is all about the conceptual design of the single shaft plastic shredding machine rotor. In this chapter three alternative concept is provided, compared and evaluated with 12 design criteria.

The fourth chapter is modeling, FEA, and optimization of the rotor components. The modeling of the components is carried out with CAD modeling on *SOLID WORK®V20R1* whereas the FEA and optimization are conducted on *ANSYS®V19R3* workbench.

In the fifth chapter, the result and discussion of the work are presented. The last chapter: Chapter six where the conclusion of the thesis is addressed and recommendation for future work is listed.

1.6. RESEARCH METHODOLOGY

To address the above-mentioned research gaps different research methodology is used. The first one is an analytical method and the second one is a numerical method. In the analytical method the calculation and derivation of the power required for shearing the given area of the plastic. In the numerical method, topology optimization and parametric optimization is covered. The research methodology flow process is given in Figure 1.2. In the modelling, technically right means, when the parts are correctly fitted to each other with perfect alignment and arrangement. The topology optimization of the blade carriage at least 15% reduction of mass is considered. In the parametric optimization the three objectives (minimization of deformation and stress, and maximization of safety factor) should be satisfied. If these objectives are satisfied the flow of the work can proceed to the next step, if not the parametric optimization should be conducted again.

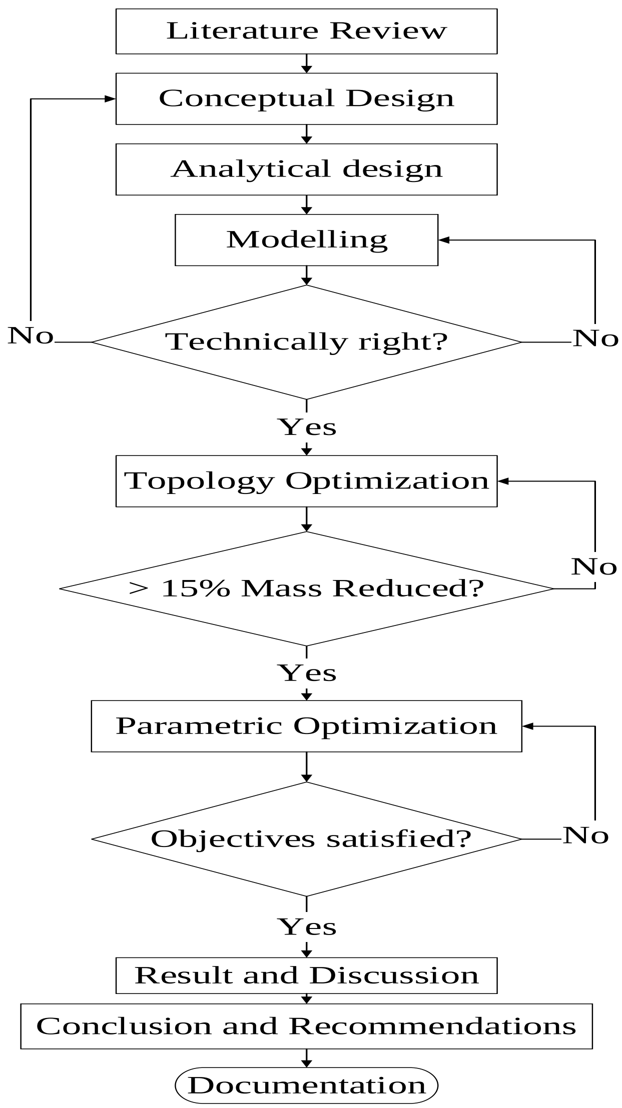


Figure 1.2: The flow chart of research methodology

CHAPTER TWO

2. OVERVIEWS ON PLASTIC MATERIALS AND SHREDDING MACHINE

2.1. THE ORIGIN AND REVOLUTION OF PLASTIC MATERIALS

The word plastic derives from the Greek πλαστικός (plastikos) meaning "capable of being shaped or molded" and, in turn, from πλαστός (plastos) meaning "molded". According to the American Chemistry Council (ACC), plastic is, "a type of synthetic or man-made polymer; similar in many ways to natural resins found in trees and other plants" 97-99% of these plastics derives from fossil fuel feedstock while the remaining 1-3% comes from bio(plant) based plastics [18]. It is usual to think that plastics are a relatively recent development but, as part of the larger family called *polymers*, they are a basic ingredient of animal and plant life. Polymers are different from metals in the sense that their structure consists of very long chain-like molecules. Natural materials such as silk, shellac, bitumen, rubber, and cellulose have this type of structure. However, it was not until the 19th century that attempts were made to develop a synthetic polymeric material and the first success was based on cellulose. The origins of commonly used plastics are (1) natural gas (2) crude oil distillation and (3) natural cellulose. Plastics generally are high polymers, which are formed either during or after their transition from a low molecular weight chemical to a high molecular weight solid material. The higher molecular weight of solid materials is a result of additives or ingredients such as fillers, plasticizers, etc. [7].

The period 1930-1940 saw the initial commercial development of today's major thermoplastics, namely: *polyvinyl chloride, low-density polyethylene, polystyrene,* and *polymethyl methacrylate.* The advent of World War II in 1939 brought plastics into great demand, largely as a substitute for materials in short supply such as natural rubber. The first decade after World War II saw the development of polypropylene and high-density polyethylene. Linear low-density polyethylene was introduced in 1978, and this introduction made it possible to produce polyethylene with densities ranging from 0.90 to 0.96. The raw materials (polyethylene) began to compete with the older plastics and even with the more traditional materials such as wood, paper, metal, glass, and leather. The demand for plastics has increased steadily. Plastics are now accepted by designers and engineers as basic materials along with the more traditional materials. The automotive industry and aerospace industry; for example, relies on plastics to reduce weight and thus increase energy efficiency [5], [7], [9].

Depending on their thermal and chemical properties there are two main categories of plastics. The first one is *"thermoplastics"* and the other one is *"thermosetting"*. *Thermoplastics* can repeatedly soften and melt if enough amount of heat is applied and then hardened on cooling, so that, they can be molded into new plastics products with or without the addition of virgin plastic. Examples of thermoplastics are *polyethylene, polystyrene,* and *polyvinyl chloride*. On the other hand, *thermosets* are irreversibly set to the desired shape when exposed to heat. They can melt and take shape only once. They are durable and hence used in automobiles and construction as well as applications such as adhesives and coatings. However, thermosets once they are formed in solid shape they cannot be reshaped to another form. Examples of thermosets are *urea-formaldehyde resin, melamine-formaldehyde, phenol-formaldehyde resins, epoxy resins, unsaturated polyesters,* and *alkyd resins polyurethanes.* They are mainly used in vehicle seats, sports equipment, electrical and electronic components [19]–[21].

Plastic materials, though cheap, available, and serve society's needs, are not very durable compared to metals. They are easily damaged. This means that they constitute a large amount of menace to the environment. Plastic as a solid waste can take the form of damaged washing bowls, jerry cans, food storage containers, footwear, buckets, plates, seats, etc. The disadvantages caused by the massive use of plastics are invidious. These plastics being synthetic rather than natural are frequently not broken down by microorganisms in the way that natural polymers are. That is, they are not biodegradable. Everywhere in cities and towns, one sees litters of discarded plastic items. They come in whole or parts. The most striking menace is the packaging plastics, especially the polythene sheets that are used for packaging water (pure water), foods, and confectioneries. They stay out there and accumulate continuously [9].

2.2. PLASTIC VALUE CHAIN AND THE PLASTIC WASTE MANAGEMENT SYSTEMS

Some plastic products have long life spans such as building and construction materials (35 years), industrial machinery (20 years), plastic products in the transportation sector (13 years)

electrical/electronic plastic products (8 years) and textiles (5 years). However, the majority have a short life cycle lasting between one day (e.g., disposable plastic cups, plates, takeaway containers, plastic bags, etc.) to three years (e.g., food and drink containers, cosmetics, agricultural film, etc.). The plastics value chain includes the full range of activities, which are required to bring a plastic product through the different phases of extracting raw materials, production, distribution to consumers, and final disposal after use [18]. Figure 1.1 summarizes this process in a descriptive way.

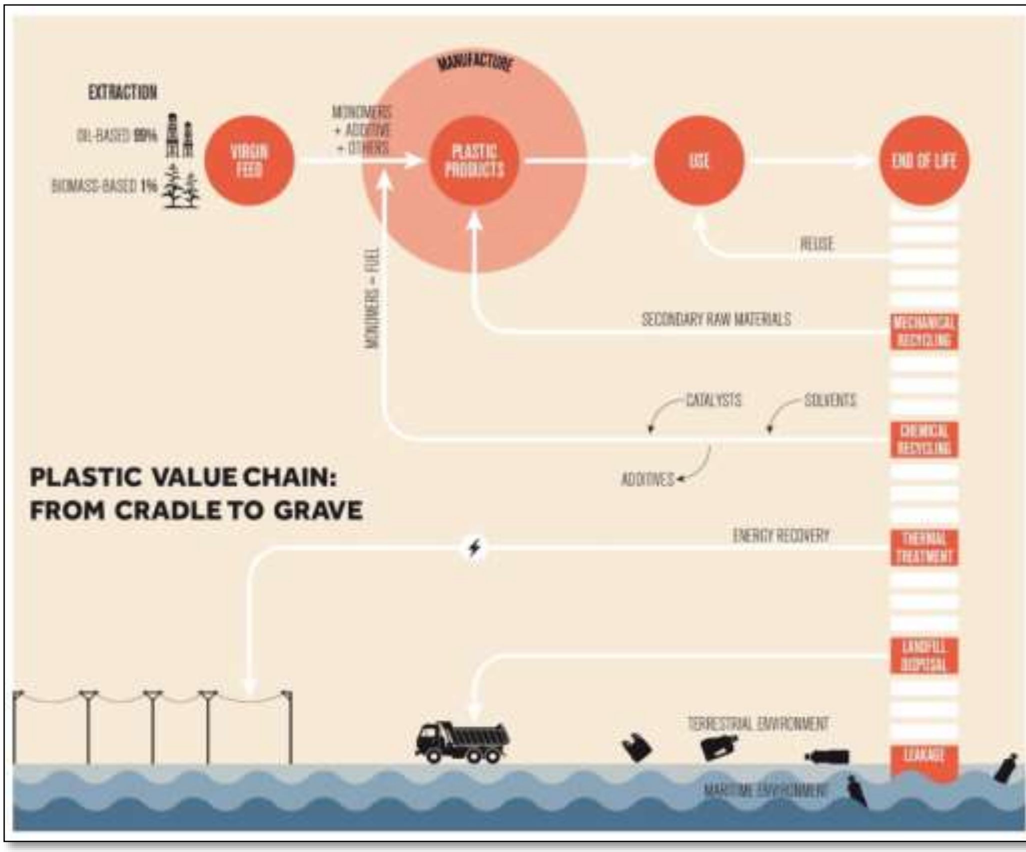


Figure 2.1: Plastic value chain [22]

Plastic material wastes are the waste generated from the used plastic products. If this waste is not handled it can take more than 500 years to decompose. Plastic pollution can unfavorably affect lands, waterways, and oceans. Living organisms, particularly marine animals, can also be affected through entanglement, direct ingestion of plastic waste, or exposure to chemicals within plastics that cause interruptions in biological functions [7]. They are also inconvenient for burning paper wastes because they do have hydrocarbons when burnt to release many toxic matters into the atmosphere. The gases released are highly carcinogenic. So, if burning is to be done, it should be carried out in a sophisticated incineration plant. But this is extremely costly and highly unmanageable in developing countries [9].

At least 8 million tons of plastic end up in our oceans every year. Floating plastic debris is currently the most abundant item of marine litter. Waste plastic makes up 40-80% of all marine debris from surface waters to deep-sea sediments [23]. Plastic has been detected on shorelines of all the continents, with more plastic materials found near popular tourist destinations and densely populated areas. The main sources of marine plastic are land-based, from urban and storm runoff, sewer overflows, beach visitors, inadequate waste disposal and management, industrial activities, construction, and illegal dumping. Ocean-based plastic originates mainly from the fishing industry, nautical activities, and aquaculture. Under the influence of solar Ultra Violet Radiation (UVR), wind, currents, and other natural factors, plastic fragments into small particles, termed microplastics (particles smaller than 5 mm) or nano plastics (particles smaller than 100 nm). Many more are probably harmed invisibly. Marine species of all sizes, from zooplankton to whales, now eat microplastics, the bits smaller than one-fifth of an inch across. The most visible and disturbing impacts of marine plastics are the ingestion, suffocation, and entanglement of hundreds of marine species. Marine wildlife such as seabirds, whales, fishes, and turtles, mistake plastic waste for prey, and most die of starvation as their stomachs are filled with plastic debris. They also suffer from lacerations, infections, reduced ability to swim, and internal injuries. Floating plastics also contribute to the spread of invasive marine organisms and bacteria, which disrupt ecosystems. One million waste plastic bottles are churned out every minute across the world while five trillion plastic bags are generated yearly, about 10 million units every minute. It is also estimated that at least eight million tons of plastic end up in the oceans every year [24]. The empirical prediction that by 2050, the world's ocean will have more plastic than fish portends far-reaching dangers and calls for drastic measures to address the menace urgently [4].

2.3. PLASTIC SHREDDING MACHINES AND THEIR CLASSIFICATION

The first generation of shredders: - Most of the first generation of the transmission mechanism is driven by a belt with low noise. The second generation of shredders: - Plastic gear rolls, because it is difficult to master the injection and shrinking process accurately of the shredder machine, resulting in the low accuracy of the gear itself. Third generation shredders: - Metal sprocket: quiet operation, low energy loss, efficient cutting, and the perfect coordination of the various components of the system achieve the compelling features. The fourth generation of shredder machines. The drive mechanism of the shredder machine is the metal gear, although the metal gear so overcomes the above drawbacks, it is difficult to avoid the impact of the metal gear and friction sound. The fifth generation of shredder: Diamond snug movement, it makes use of alloy steel materials, quenching process of a metal tool, completely Computer Numerical Control (CNC) machining technology, and the workmanship guarantee transmission installation accuracy. The sixth generation of shredders (modern): - Currently, the high-tech multimedia high series grinder has the high technology content which can be used to broken Compact Disk- Read Only Memory (CD-ROM), floppy disk, tape, video, etc. and the embedded button panel with a protective film ensure the function of the way forward, rewind, stop, and full stop. In the modern world, we pay attention to care for the quality of life. Figure 2.2 below shows the parts of the plastic shredding machine.

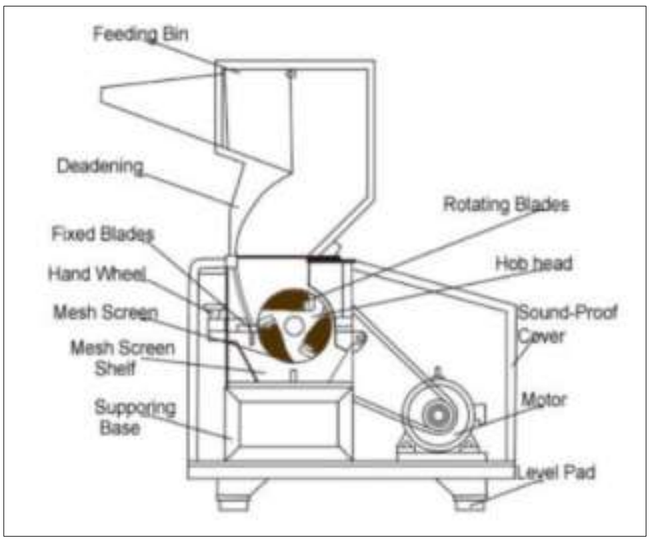
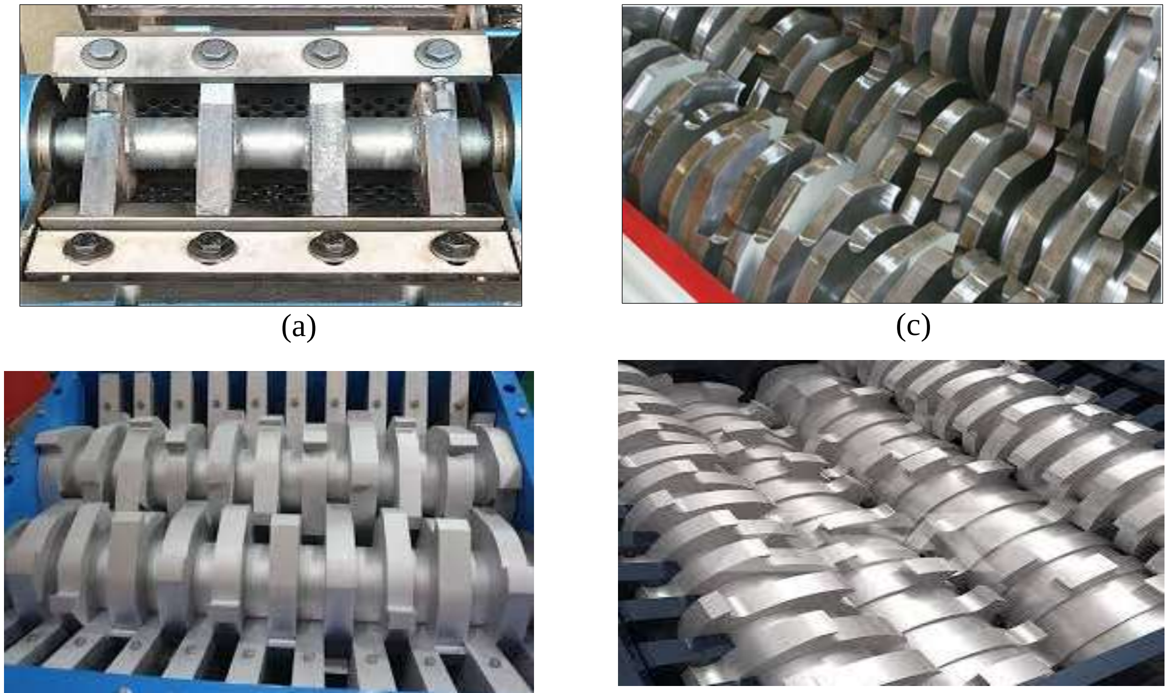


Figure 2.2: The main components of plastic shredding machine [22]

1. Depending on the number of shafts

Depending on the arrangement of the shaft plastic shredder is categorized as horizontal and vertical shaft. Depending on the number of shafts it is divided into single-shaft, double-shaft, triple-shaft, and four-shaft shredder. Figure 2.3 presents this classification.



(a) (c) (b) (d)

Figure 2.3: Types of plastic shredding machine a) Single shaft, b) Double shaft, c) Triple shaft, d) Four shaft

1. Depending on the number of the stationary blade and rotating blade

The number of blades used in shredding machines is another factor to categorize plastic shredding machines. Two stationary blades and three rotating blades are commonly used, and also depending on the number of rotating blades two, three, five, seven are commonly used. For example, in Figure 2.4 below two stationary and three rotating blades are given.

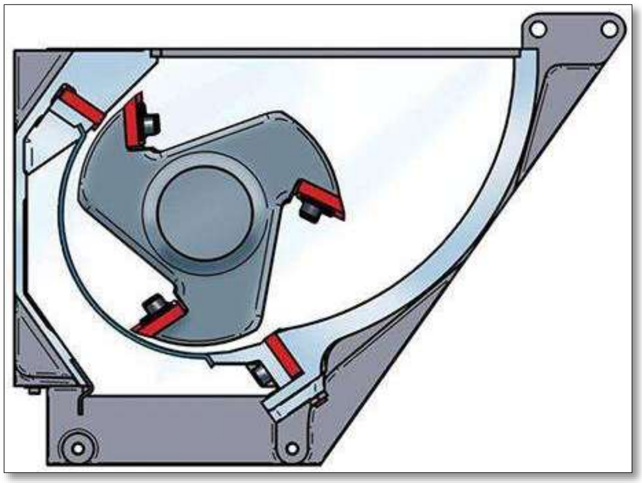
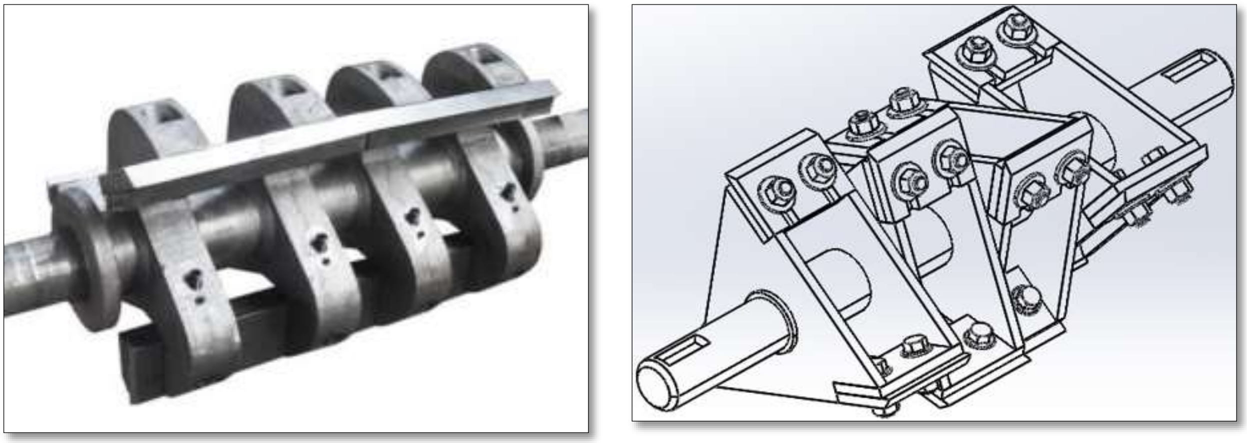


Figure 2.4: Two stationery, three rotating blade arrangement

2. Depending on the arrangement of the blade

Depending on the arrangement of the blade it is divided into flat, inclined, and staggered arrangements. Such arrangement is mainly depending on the designer's interest and application. Figure 2.3 (a), Figure 2.5 (a) and Figure 2.5 (b) show flat, inclined, and staggered blade arrangement respectively.



(a) (b)

Figure 2.5: (a) Inclined arrangement (b) Staggered arrangement (Researcher)

CHAPTER THREE

3. LITERATURE REVIEW

In this chapter the work related to the topic is reviewed. The reviewed papers are categorized by geographically to clearly show the domestication of the area. It is classified into World context except Africa, African context and Ethiopian context.

3.1. THE FORMER DESIGN AND DEVELOPMENT OF PLASTIC SHREDDING MACHINES

3.1.1. World scenario excluding Africa

The Master's Thesis taken at Lund University (Sweden) presented the modified conceptual design version of a single shaft plastic shredder previously designed by Precious Plastic [23]. Even if the paper new conceptual design it doesn't compared different. The type of shafts used is hexagonal shaft type, which is used for stage 1 and stage 2 (Figure 3.6). Even if the design is easy for disassembly and maintenance the strength of the parts is not analyzed with FEA. In the same year from India this machine is developed with a different arrangement [24]. Both the papers used a double jaw/tooth carriage which has lower performance than triple and above numbers of teeth. This is because, with in one revolution the number of plastics bitten depends on the number of stationary and rotating blades provided for the design. For example, the blade with double stationary and double rotating blades (2x2 design) can hit the plastic 4 times within one revolution. Accordingly, 2x3 design can hit the plastic 9 times within single revolution.

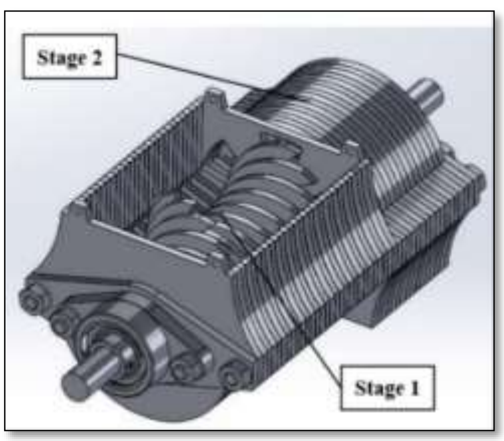


Figure 3.1: Shredder rotor developed by [23]

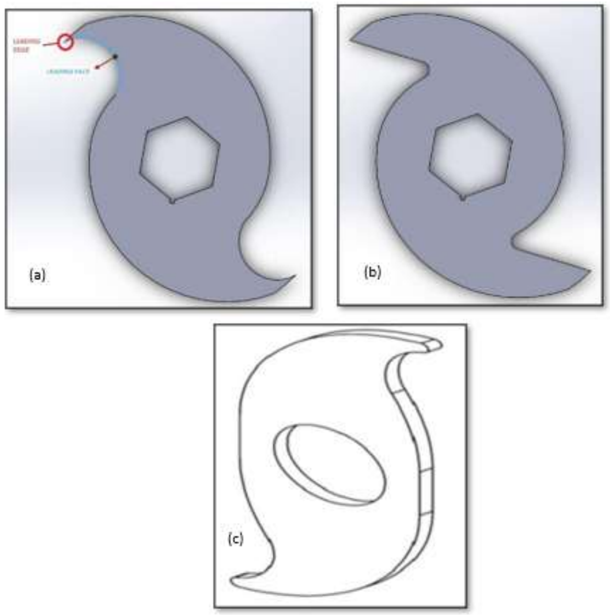


Figure 3.2: Blade design proposed in (a) Precious plastic (b) [23] (c) [24]

3.1.2. African scenario excluding Ethiopia

From Nigeria also developed the vertical arrangement types of single shaft shredder [25,26]. The former used both fixed and rotating blades with vertically pushing pistons were as the later used only rotating blades for crushing purposes. From the same country, another paper presents the conceptual design and FEA of double shaft plastic shredder machine [27]. In this paper, the rotor of the shredder is analyzed against torsional load.

3.1.3. Ethiopian scenario

In the context of Ethiopia, there is no satisfactory work on plastic shredding machine design and analysis. The only work found are [28], [29]. Bethlehem worked on modeling solid waste shredding cutter using FEM [29]. In her work, she proposed four different types of cutter models, then compared with and recommended one of the best models (Figure 2.8). The Von-Mises stresses of the model 1 up to 4 are 3.92 x 10^7 N/m^2, 3.53 x 10^7 N/m^2, 4.4 x 10^7 N/m^2, and 1.06 x 10^8 N/m^2 respectively.

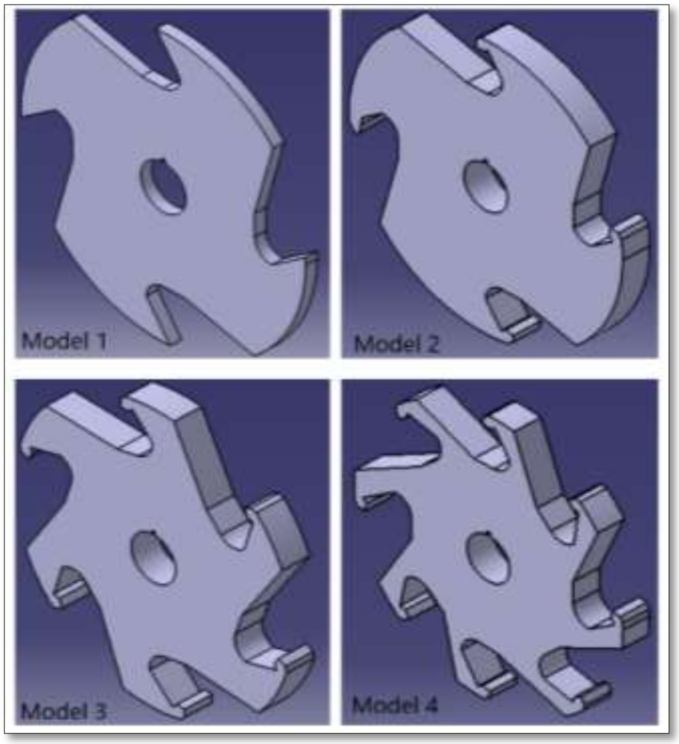


Figure 3.3: The model proposed by [29]

Tegegne et l developed a dual shaft, multi-blade waste plastic shredder [30]. The geometry of the blade they used is a triple jaw type (Figure 3.9). The performance of his machine with a 2 hp electric motor showed 11 kg/hrs. of shredded flakes of plastic wastes at 65 RPM.

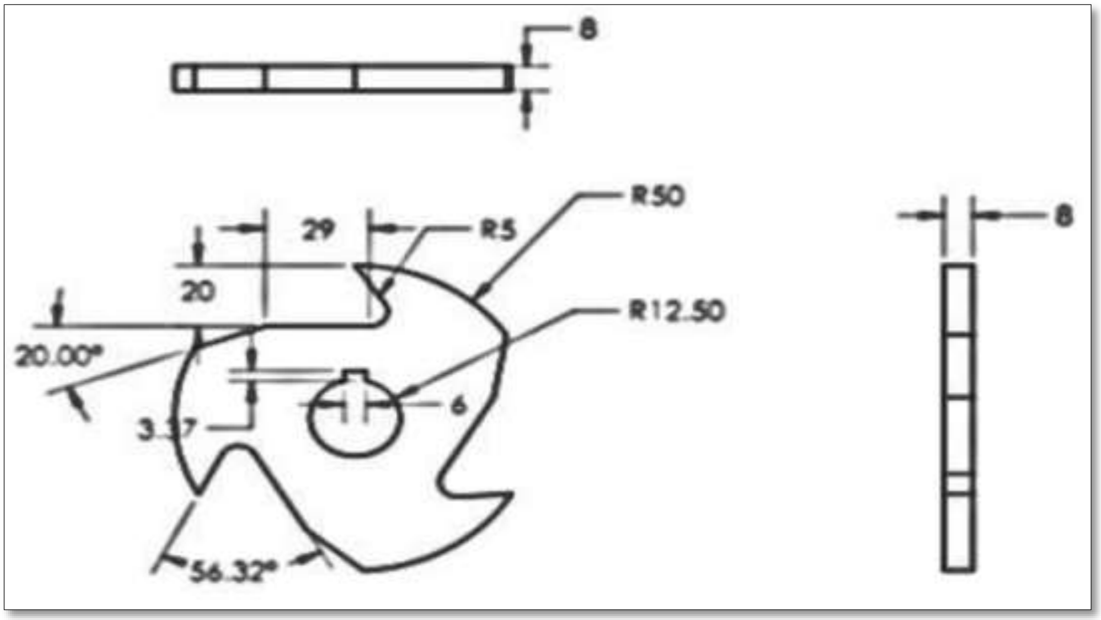


Figure 3.4: Triple jaw blade proposed by [30]

3.2. LITERATURE SUMMARY AND RESEARCH GAP

Most of the researchers mentioned and detailed above have developed shredder which has different rotor arrangement. Some of them used double jaw [26], [27], triple jaw [29], quadric jaw [29]. As it is discussed in the literature double jaw rotor blade has lower performance than triple and above numbers of blades [15]. This is due to the fact that as the number increases the number of cut per revolution also will increase. However, if increasing the number of the blade may increase performance if it is too many it may also hinder the feeding of plastic material into the shearing area. Therefore, in this work triple jaw blade carriage is proposed by considering the sometimes the machine can shredd material that can occupy large volume like jar can. Another problem of former development is that the blade carriage and the shaft are welded together which makes all the assembly useless if one component fails. To solve this problem suggesting a detachable design is recommended, which is considered in this work.

Considering all the necessary design points the papers reviewed are summarized as on Table 3.5.

Table 3.1: Sorted papers by criteria

Paper	Blade Type	Conceptual Design	FEA	Topology Optimization	Parametric Optimization	Fabrication
23	Double jaw	Conducted	Not conducted	Not conducted	Not conducted	Conducted
24	Double jaw	Conducted	Not conducted	Not conducted	Not conducted	Not conducted
27	Double	Conducted	Conducted	Not conducted	Not conducted	Conducted
29	Quadri jaw	Conducted	Conducted	Not conducted	Not conducted	Not conducted
30	Triple jaw	Not conducted	Not conducted	Not conducted	Not conducted	Not conducted

The following points are extracted as a research gab:

- The conceptual design of the rotor considered in the papers is not thorough, they didn’t consider different variety of concepts.
- The types of blades used has low production efficiency, as the number of blades increases the number of times the plastic is sheared will increase too. For example if two rotating and two stationary blades are there, the plastic can be sheared four and six times per revolution respectively.
- It is possible to make the rotor part detachable
- There is no optimization tool is used in the design process

CHAPTER FOUR

4. CONCEPTUAL DESIGN OF THE ROTOR

This chapter is all about conceptual design of shredder rotor. In this conceptual design, generic product design technique and FEA is used to compare and select appropriate rotor concept variant. Then the selected concept is further used in optimization.

4.1. INTRODUCTION

Product development is the process of creating a new product to be sold by a business enterprise to its customers. Design refers to those activities involved in creating the styling, look and feel of the product, deciding on the product's mechanical architecture, selecting materials and processes, and engineering the various components necessary to make the product work. Development refers collectively to the entire process of identifying a market opportunity, creating a product to appeal to the identified market, and finally, testing, modifying, and refining the product until it is ready for production [30]. The generic product development process consists of six phases (Figure 4.1).

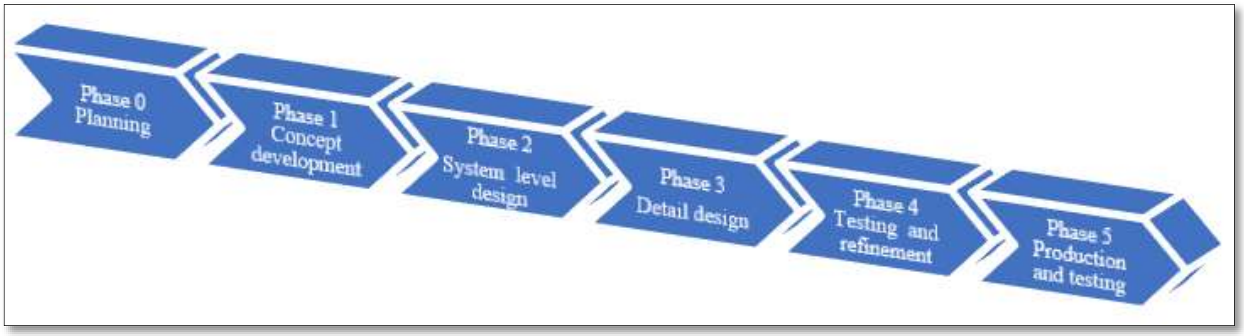


Figure 4.1: Generic product development Process

Phase 0: Planning: The planning activity is often referred to as "phase zero" because it precedes the project approval and launch of the actual product development process. This phase begins with opportunity identification guided by corporate strategy and includes an assessment of technology developments and market objectives. The output of the planning phase is the project mission statement, which specifies the target market for the product, business goals, key assumptions, and constraints.

Phase 1: ***Concept development:*** A concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, and analysis of competitive products, and an economic justification of the project.

Phase 2: ***System-level design:*** The system-level design phase includes the definition of the product architecture, decomposition of the product into subsystems and components, and preliminary design of key components. The output of this phase usually includes a geometric layout of the product, a functional specification of each of the product's subsystems, and a preliminary process flow diagram for the final assembly process.

Phase 3: ***Detail design:*** The detail design phase includes the complete specification of the geometry, materials, and tolerances of all of the unique parts in the product and the identification of all of the standard parts to be purchased from suppliers. A process plan is established and tooling is designed for each part to be fabricated within the production system. The output of this phase is the control documentation for the product—the drawings or computer files describing the geometry of each part and its production tooling, the specifications of the purchased parts, and the process plans for the fabrication and assembly of the product.

Phase 4: ***Testing and refinement:*** The testing and refinement phase involves the construction and evaluation of multiple preproduction versions of the product order to identify necessary engineering changes for the final product

Phase 5: ***Production ramp-up:*** In the production ramp-up phase, the product is made using the intended production system. The purpose of the ramp-up is to train the workforce and to work out any remaining problems in the production processes. Products produced during production ramp-up are sometimes supplied to preferred customers and are carefully evaluated to identify any remaining flaws.

4.2. DEFINITION OF CONCEPTUAL DESIGN

A product concept is an approximate description of the technology, working principles, and form of the product. It is a concise description of how the product will satisfy the customer's needs. A concept is usually expressed as a sketch or as a rough three-dimensional model and is often accompanied by a brief textual description. The degree to which a product satisfies customers and can be successfully commercialized depends on a large measure of the quality of the underlying concept. Conceptual design is commonly defined as "… the phase of design that requires the greatest creativity, involves the most uncertainty, and requires coordination among many functions in the business organization. The goal in this phase is to validate the need, produce several possible solutions, and evaluate the solutions based on physical reliability, economic worthwhileness, and financial feasibility" [30]–[32]. The procedures of conceptual design are given in Figure 4.2.

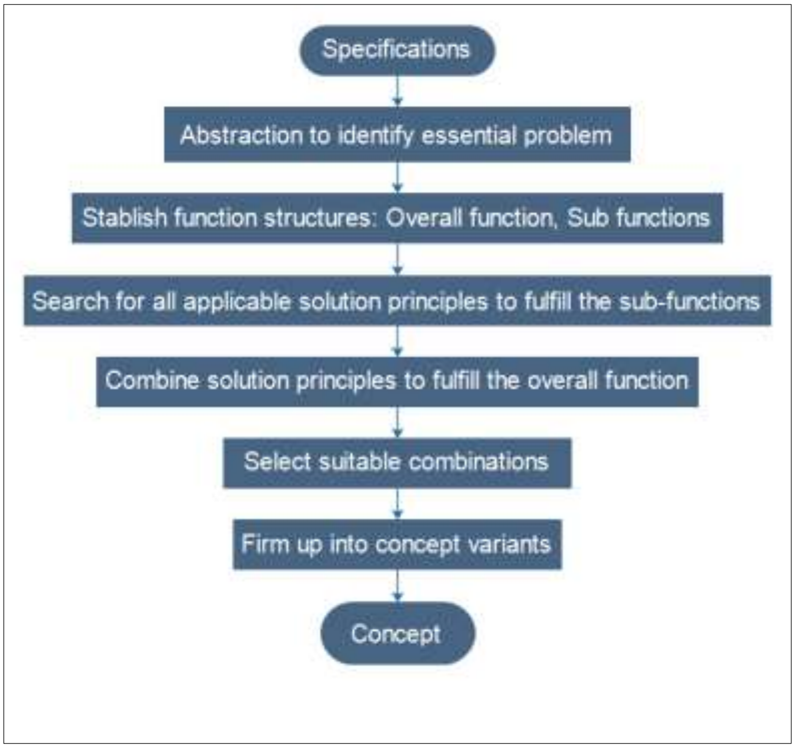


Figure 4.2: Conceptual design procedures

4.3. CONCEPT GENERATION AND SELECTION OF SHREDDER ROTOR

For shearing mechanism there are various concept that can be used as alternative solutions. By revising several developed rotor types three broad categories of concepts are provided for comparison (Table 4.1). Those concept variants are only subjected to single shaft types of rotors. Their variations are like length and arrangements of the blades. Various multi-criteria decision making (MCDM) methods exists to aid concept selection. However, four commonly known MCDM methods are Pugh's concept selection (Pugh) [33]–[35], Weighted Rating Method (WRM) as presented by Ulrich and Eppinger [30], Saaty's Analytical Hierarchy Process (AHP)

[36], and Roy's Electre III (Electre) [37]. As [38] recommends Pugh MCDM for less complicated situation it is used in this study.

Table 4.1: Concepts for a shearing mechanism

Concepts	**Concept I:** Flat shape	**Concept II:** Scissor shape	**Concept III:** Staggered shape
3D figure			
Description	The cutting blade is flat for the entire length	The cutting blade is inclined	The cutting blade is a short flat

4.3.1. Identifying evaluation criteria

High efficiency, simplicity of technology, economy, and material availability are considered as general objectives of evaluation criteria which are further classified into their respective specific objectives. There are 12 unique criteria in which the concept variants will be compared. Table 4.2 summarizes these evaluation criteria with their respective identification codes. For example, under the general objective of higher efficiency, low shearing force, and low power consumption are the specific objectives and likewise, the other general objectives have their specific objectives.

Table 4.2: General and specific objectives of evaluation criteria

No	Code	General objectives	No	Code	Specific objectives
1	O_1	Higher efficiency	1	O_{11}	Low shearing force
			2	O_{12}	Lower power consumption
2	O_2	Simplicity of technology	3	O_{21}	Ease of manufacturing
			4	O_{22}	Uniform wear of teeth
			5	O_{23}	Ease of maintenance
			6	O_{24}	Low noise
3	O_3	Economy	7	O_{31}	Low manufacturing cost
			8	O_{32}	Low running cost
			9	O_{33}	Low maintenance cost
4	O_4	Material	10	O_{41}	Availability on the market
			11	O_{42}	Corrosion resistance
			12	O_{43}	Hardness

4.3.2. Criteria ranking and weighting

The most commonly used ranking method is the matrix proposed by Pugh [35]. This matrix has become known as the binary dominance matrix. In this method, a matrix is formed, as shown in Table 4.3, with the criteria listed on both the vertical and horizontal axes. A 1 or 0 is placed in each box of the matrix depending upon the relative importance of the pair of criteria. In the first row, decisions are made regarding whether ease of operation is more or less important than the remaining 11 criteria. If ease of operation is more important than another criterion, 1 is assigned, if less important, 0 is assigned. The numbers of 1s in the matrix is calculated using the formula:

$$x = 0.5n(n - 1)$$

where x is the number of 1s, n is the total number of criteria. By inserting the known value (n = 12), the following result is obtained

$$x = 0.5x12(12 - 1) = 66$$

Table 4.3: Binary dominance matrix for criteria weighting

Criteria	O_{111}	O_{112}	O_{121}	O_{122}	O_{123}	O_{124}	O_{131}	O_{132}	O_{133}	O_{141}	O_{142}	O_{143}	Total	Rank	Weight
O_{111}	-	0	0	0	0	1	0	0	0	0	1	1	3	9	0.05
O_{112}	1	-	0	1	0	1	0	0	0	1	1	1	6	6	0.09
O_{121}	1	1	-	1	1	1	1	1	1	1	1	1	11	1	0.17
O_{122}	1	0	0	-	0	1	0	0	0	0	1	1	4	8	0.06
O_{123}	1	1	0	1	-	1	0	0	1	1	1	1	8	4	0.12
O_{124}	0	0	0	0	0	-	0	0	0	0	1	1	2	10	0.03
O_{131}	1	1	0	1	1	1	-	1	1	1	1	1	10	2	0.15
O_{132}	1	1	0	1	1	1	0	-	1	1	1	1	9	3	0.14
O_{133}	1	1	0	1	0	1	0	0	-	1	1	1	7	5	0.11
O_{141}	1	0	0	1	0	1	0	0	0	-	1	1	5	7	0.08
O_{142}	0	0	0	0	0	0	0	0	0	0	-	0	0	12	0.00
O_{143}	0	0	0	0	0	0	0	0	0	0	1	-	1	11	0.02
												Total	66		1

4.3.3. Comparing concept variants

Based on the summation rule shown, it is possible to assess concept variants in several ways. The most commonly used way of comparing concept variants is based on the maximum value of rate determination. The rate determination is carried out by using the weighted overall values calculated earlier and the percentage satisfaction of concept variants for achieving corresponding evaluation criteria (Table 4.4).

Concept III gets a higher percentage than the rest of the Concept variant. Therefore, it is selected for the shearing mechanism of the shredder to be designed.

Table 4.4: Comparison of concept variants

No	Criteria	Rank	Weighting	Concept I	Concept II	Concept III
1	Low shear force	8	0.0606	55%	80%	75%
2	Lower power consumption	6	0.0909	63%	70%	65%
3	Ease of manufacturing	2	0.1515	65%	50%	75%
4	Uniform wear of teeth	10	0.0303	72%	65%	90%
5	Ease of maintenance	4	0.1212	75%	55%	80%
6	Low noise	12	0	65%	68%	65%
7	Low manufacturing cost	1	0.1666	60%	55%	75%
8	Low running cost	5	0.106	65%	75%	80%
9	Low maintenance cost	3	0.1363	85%	75%	86%
10	Mat. availability on market	7	0.0757	60%	60%	60%
11	Corrosion resistance	9	0.0454	50%	50%	50%
12	Hardness	11	0.0151	70%	70%	70%
			Total result	65.42%	64.42%	66.75%

4.4. COMPARATIVE STATIC ANALYSIS OF THE THREE ALTERNATIVE BLADE CARRIAGES

The main aim of this analysis is to compare and select the proper types of fastening mechanisms between the shaft and the blade carrier. Three alternatives were used. *The first one* is using a cylindrical shaft welded on the blade carriers. *The second one* is using a hexagonal shaft geometrically inserted into the same hexagonal shape blade carrier and fastened by a bolt at one end. *The third alternative* is somewhat the same as the second one but the geometry used is a splined shaft with spline shape hub blade carrier. For simplification of the assembly, only a single blade carrier was used for this static structural analysis. To idealize the practical application and also applying the load and boundary condition to the proper area the full length of the shaft is used. For further analysis, the full assembly will be used. The material used for all the parts is structural steel as the aim is not material optimization but, comparison of the mechanisms. The material that is used in this analysis is static structural steel, as the analysis is not checking the component at the worst case simply the material is selected.

The model geometry and meshing

The cylindrical shaft assembly the blade carrier jaw is welded by a 10 mm radius on the cylindrical shaft. On Ansys, the contact between the shaft and the carrier is set to rough and the rest are set to bonded contact. But for hexagonal and splined shafts the contact that is set to rough is only the contact between the shaft and the carrier. This is because, the blade carriage is free to move in the direction of the axis of the shaft.

The imported models for cylindrical, hexagonal, and splined shafts from solid work are given on Figures 4.4. For all models, the setting of the meshing is set to its default status except span angle center, which is set to fine. Figures 4.5 show the meshing of the three-attachment mechanism used for attaching the shaft with the blade carriage. The tetrahedron type of element is used in the meshing with 5 mm element size.

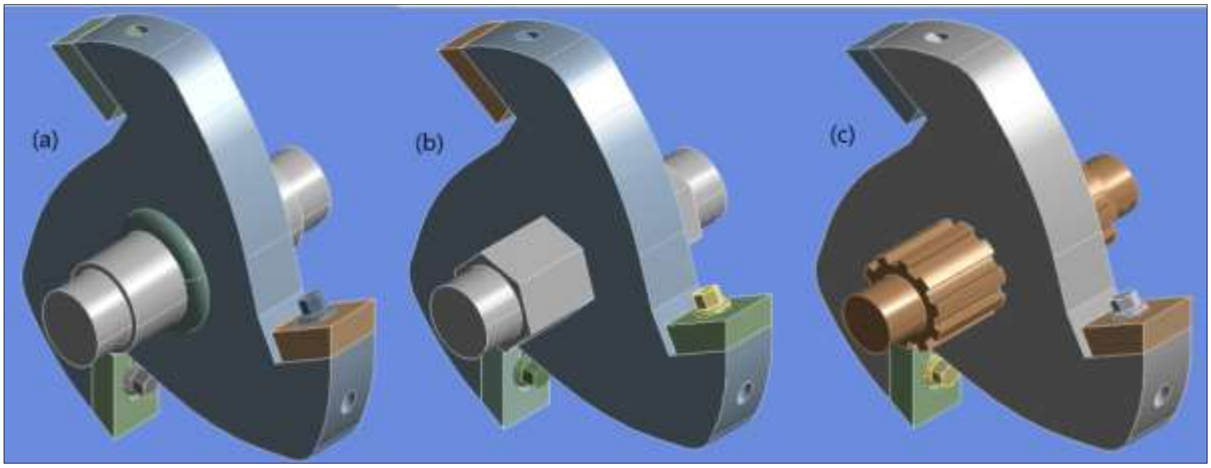


Figure 4.3: Types of shafts (a) Cylindrical, (b) Hexagonal and (c) Spline

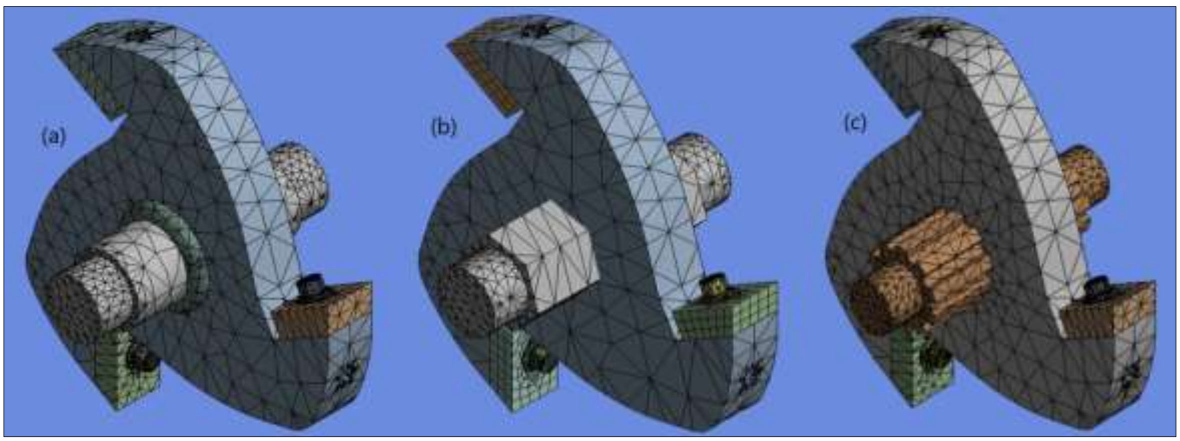


Figure 4.4: Meshing (a) Cylindrical, (b) Hexagonal and (c) Spline

- **Boundary conditions and loads for analysis**

The boundary condition for all three shafts given in Figure 4.6. As it is shown on the figure for each model both ends of the assembly is set to fixed boundary condition and 62 MPa (Tensile Strength of PVC) load is also applied at the tip of the blade.

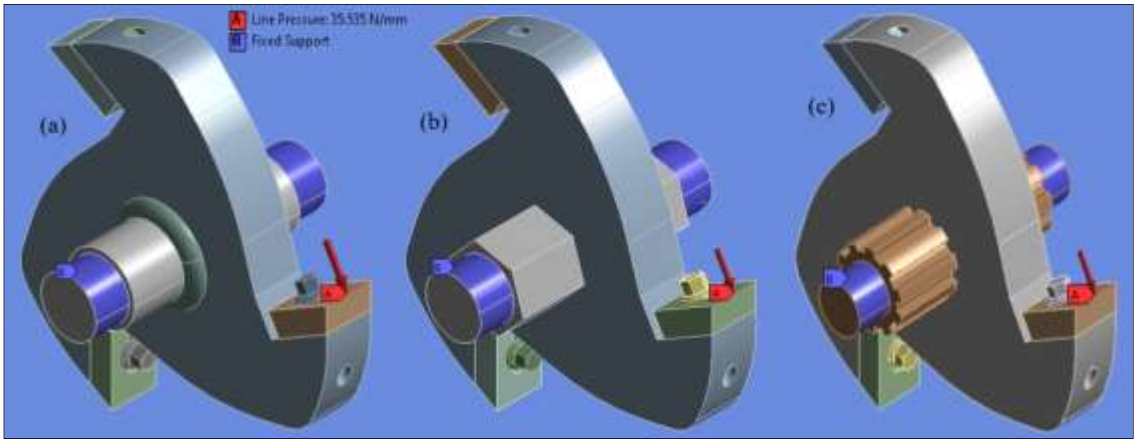


Figure 4.5: Loading and boundary condition (a) Cylindrical (b) Hexagonal and (c) spline

- **Static structural results**

The result of the three-attachment mechanism of the blade carriage to the shaft is presented below.

1. Total deformation

As it is seen from Figure 3.6-3.9 the maximum deformation is happened at the tip of the blade, and the lowest is at the shaft. The maximum deformation of the three mechanisms is 0.0399 mm for cylindrical, 0.0316 mm for hexagonal and 0.0283 mm for spline shaft.

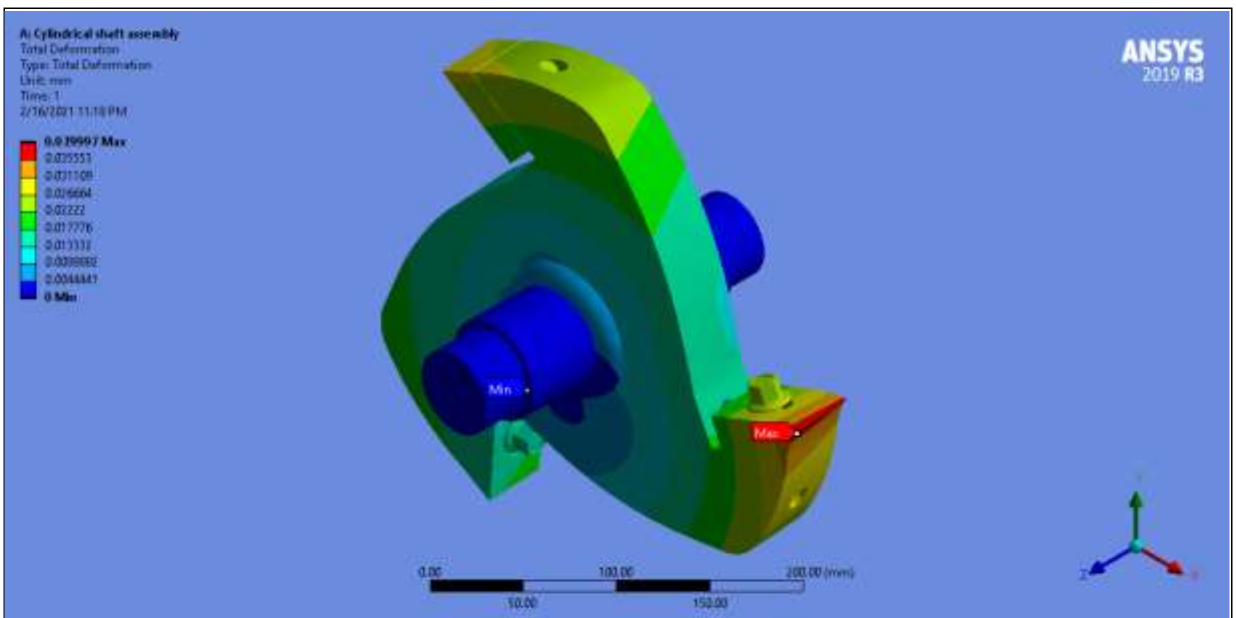


Figure 4.6: Total deformation result for cylindrical shaft-carriage assembly

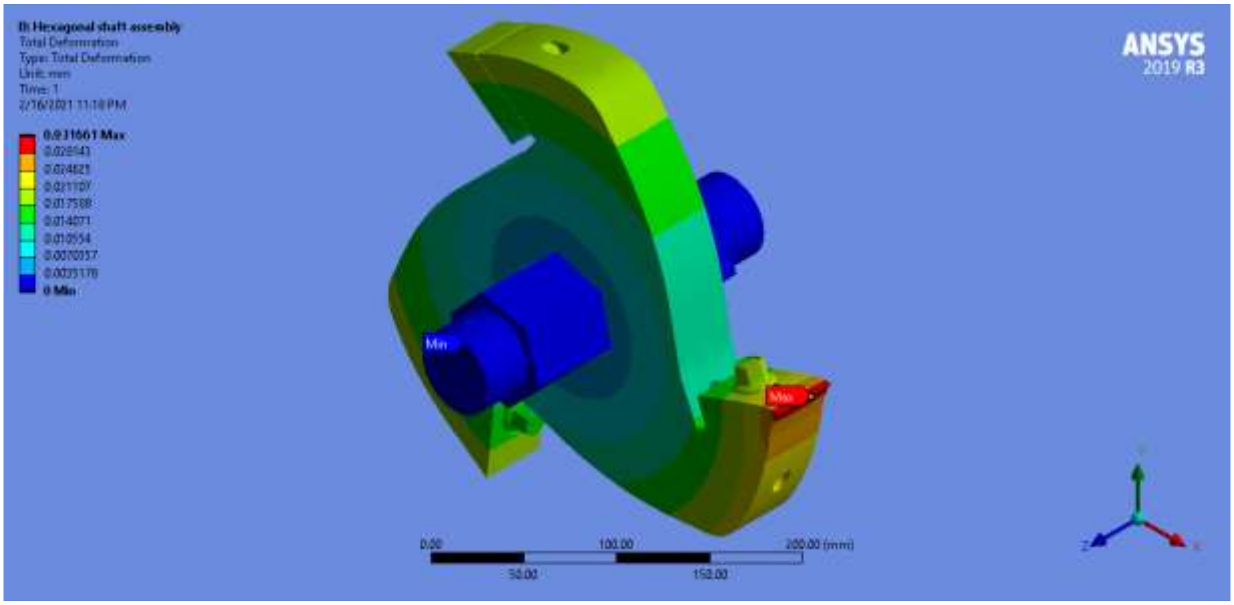


Figure 4.7: Total deformation result for hexagonal shaft-carriage assembly

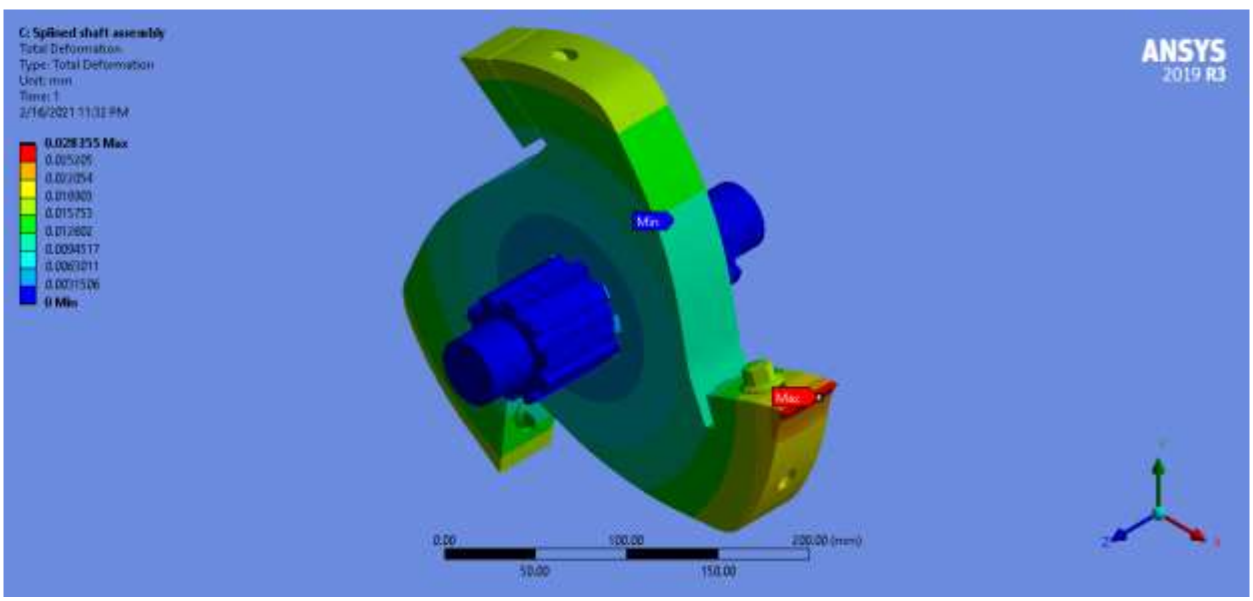


Figure 4.8: Total deformation result for splined shaft-carriage assembly

2. Equivalent Von-Mises stress

The maximum stress encountered in cylindrical shaft model happens at the joint between the shaft and the carriage which is 216.92 MPa. Whereas, for the hexagonal and splined shaft it happens at the tip of the blade which is 45.483 MPa, and 45.479 MPa respectively.

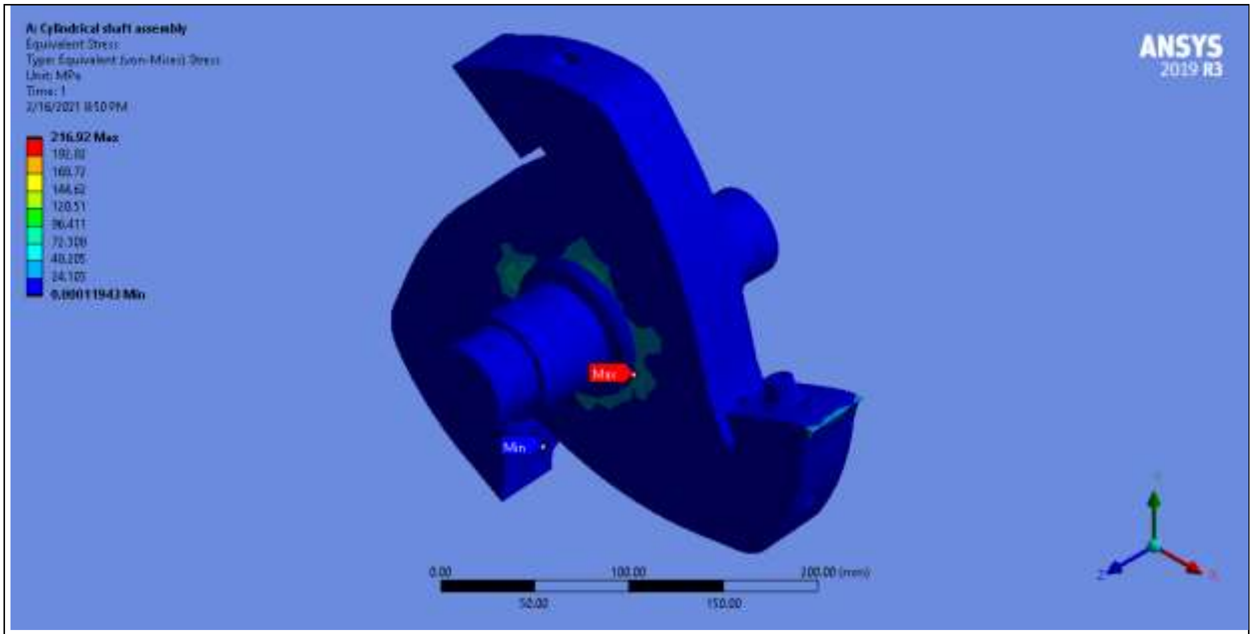


Figure 4.9: Equivalent stress result for cylindrical shaft-carriage assembly

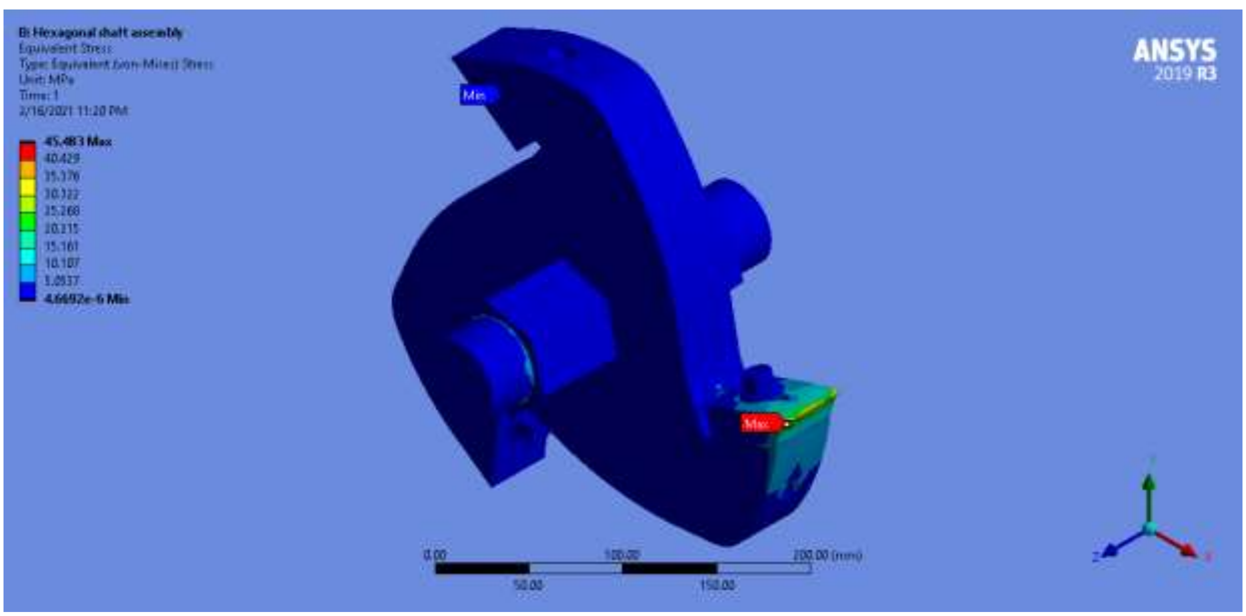


Figure 4.10: Equivalent stress result for hexagonal shaft-carriage assembly

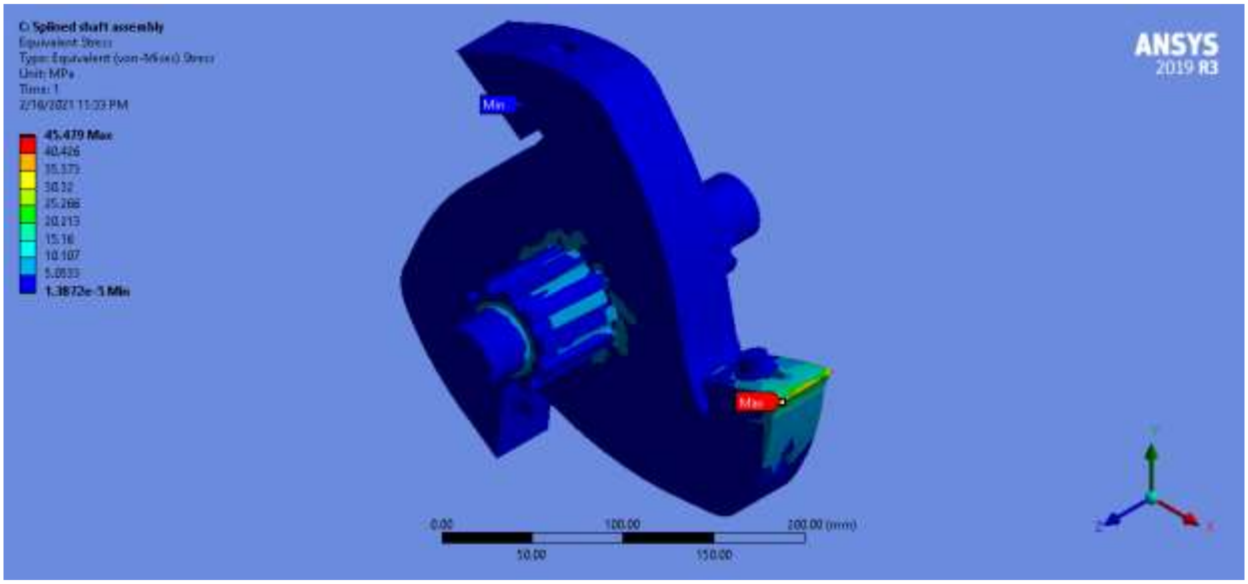


Figure 4.11: Equivalent stress result for splined shaft-carriage assembly

Table 3.5 summarizes the result of deformation, and stress of the three of the mechanisms.

Table 4.5: The result summary of shaft comparison

No	The attachment mechanism	Total Deformation	Von-Mises stress
1	Cylindrical shaft	0.0399 mm	216.92 MPa
2	Hexagonal shaft	0.0316 mm	45.483 MPa
3	Splined shaft	0.0283 mm	45.479 MPa

In figure 3.12 below the result presented in Table 3.5 is represented by bar chart for visualization.

As it is presented on Table 4.12 the minimum total deformation and Von-Mises stress happened for splined shaft assembly. Therefore, a splined shaft should be used for the highest strength. But for design and manufacturing simplicity one can recommend cylindrical shaft welded upon the carriage. Figure 4.12 shows the simplicity and strength order of the types of shafts. Accordingly, the less strong shaft type is the cylindrical one and the high strongest shaft type is the splined one. In contrast, for design and manufacturing simplicity the best shaft-carriage attachment mechanism cylindrical shaft which is welded up on carriage by a 10 mm radius weld fillet and the worst one is splined shaft simply inserted and welded into the carriage without welding.

When closely observed hexagonal and splined shaft have closer result. By considering the simplicity of design hexagonal shaft is more appropriate design than splined shaft. However,

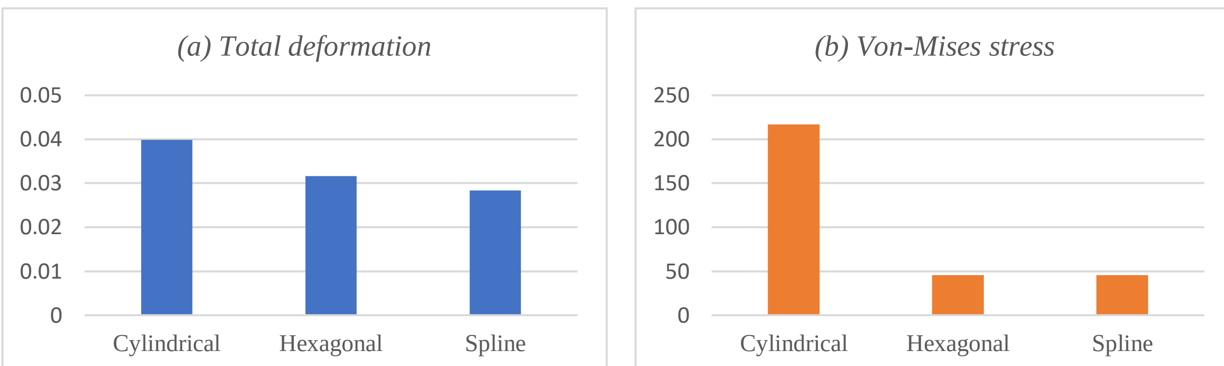


Figure 4.12: Representation of the result in bar chart (a) Total deformation (b)Von-Mises stress

hexagonal shaft has a problem on technical points of view. This is because when the carriage is consecutively inserted on to the shaft the gab of the jaw that created between two nearby carriage is too wide. This creates the engagement of two or more rotating jaw with stationary blades. Therefore, considering the strength and technical consideration splined shaft is proposed as one of the rotor parts.

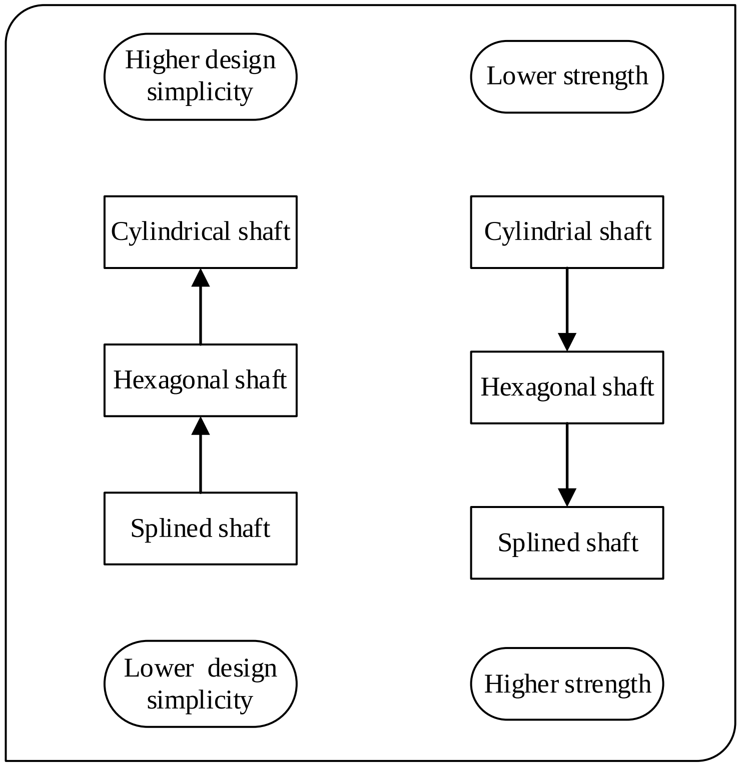


Figure 4.13: The simplicity and strength order of the shaft type

CHAPTER FIVE

5. MODELLING, FEA, AND OPTIMIZATION

5.1. APPROPRIATE MATERIAL SELECTION FOR THE ROTOR

The different types of steel materials used for this optimization are carbon steel, alloy steel, and stainless steel. Their characteristics and properties are discussed below.

Carbon Steels only contain trace amounts of elements besides carbon and iron. This group is the most common, accounting for 90% of steel production. carbon steel is divided into three subgroups depending on the amount of carbon in the metal: low carbon steels/mild steels (up to 0.3% carbon), medium carbon steels (0.3–0.6% carbon), and high carbon steels (more than 0.6% carbon). Cold-drawn carbon steel is typically numbered with the prefix "10" in the American Iron and Steel Institute (AISI) numbering system followed by two numbers that represent the nominal percentage of carbon in the product (up to 100 %). For example, C1045 has 0.45% carbon. C1045 is medium carbon steel which is stronger than C1018. Due to its strength, it is selected for this analysis [39].

In this analysis, ***Alloy steels*** contain alloying elements like nickel, copper, chromium, and/or aluminum. These additional elements are used to influence the metal's strength, ductility, corrosion resistance, and machinability. Chrome alloy steels, such as 4130, 4140, and 4340 are so named because chromium content is higher (around 1%), and is the primary alloying element. For example, 4140 has 0.40% of carbon and 0.1% of chromium. In this comparative analysis, alloy steel 4340 is used [39].

Stainless Steels contain 10–20% chromium as their alloying element and are valued for their high corrosion resistance. These steels are commonly used in medical equipment, piping, cutting tools, and food processing equipment. Type 316-Austenitic (chromium-nickel stainless class) stainless steel containing 0.2%-0.3% molybdenum (whereas type 304 has none). The inclusion of molybdenum gives 316 greater resistances to various forms of deterioration. Table 5.3 presents the specific carbon steel, alloy steel, and stainless steel used for this analysis [39].

Table 5.1: The mechanical properties of a material selected [39]*]*

Property	AISI 1045 steel (Cold rolled)	AISI 4340 alloy steel	Type 316 stainless steel
Elastic Modulus	205 GPa	205 GPa	200 GPa
Poisson's Ratio	0.29	0.32	0.265
Shear Modulus	80 GPa	80 GPa	82 GPa
Mass Density	7850 kg/m^3	7850 kg/m^3	8027 kg/m^3
Tensile Strength	625 MPa	745 MPa	485 MPa
Yield Strength	530 MPa	710 MPa	170 MPa

Due to its strength, AISI 4340 is recommended for the rotor.

5.2. FINITE ELEMENT ANALYSIS

The Finite Element Analysis (FEA) is a numerical method for solving problems of engineering and mathematical physics. Because of its diversity and flexibility as an analysis tool, it is receiving much attention in almost every industry. This method of analysis is required for a complicated element with complicated geometries, loadings, and material properties that cannot be solved in the analytical method. Further, in certain problems, the concept of FEA is a method of solving unknown variables by approximation. The FEA has become a powerful tool for numerical solutions to a wide range of engineering problems. This certain problem solved in FEA is by splitting up into many smaller areas or volumes, which is named as Finite element and the two-dimensional model of spanner to be divided is named as discretization and the assembly of the elements is named as Mesh. The discretization of elements can be of various shapes, in one-dimension two-dimensional analysis it can be quadrilateral or triangular, and in three dimensions can be wedge-shaped (pentahedral), tetrahedral or brick-shaped (hexahedral) [28].

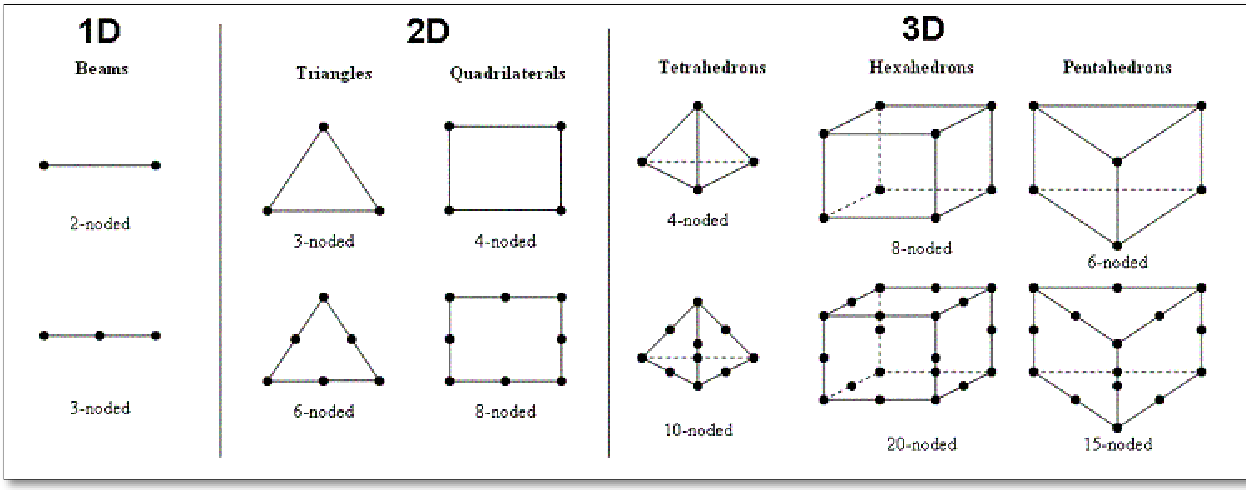


Figure 5.1: The element type classification in discretization

To conduct FEA, the following procedure is required in general:

1. Divide the Computer-Aided Design (CAD)/geometric model into pieces to create a "mesh" (a collection of elements with nodes and elements, Figure 5.1).
2. Describe the behavior of the physical quantities on each element.
3. Connect (assemble) the elements at the nodes to form an approximate system of equations for the entire model.
4. Apply loads and boundary conditions (e.g., to prevent the model from moving).
5. Solve the system of equations involving unknown quantities at the nodes (e.g., the displacements).
6. Calculate the desired quantities (e.g., strains and stresses) at elements or nodes.

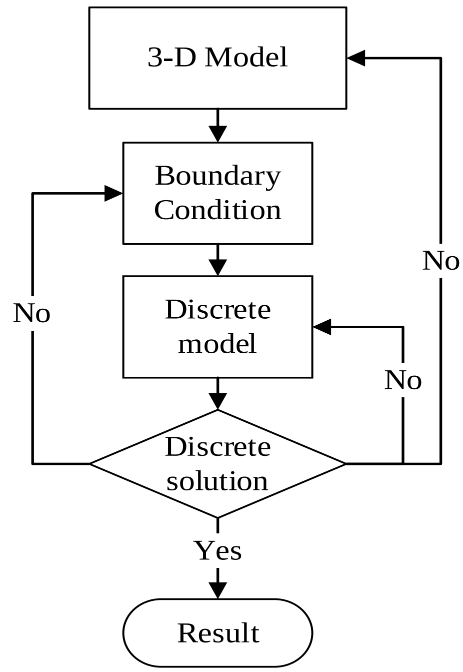


Figure 5.2: Finite element method procedure

In commercial FEA software, this procedure is typically rearranged into the following phases:

1. Preprocessing (build FEM models, define element properties, and apply loads and constraints)
2. FEA solver (assemble and solve the FEM system of equations, calculate element results)
3. Postprocessing (sort and display the results)

Before going to FEA, it is better to calculate the force required to cut a given thickness and width of plastic. As the strength of plastic varies from type to type the tensile strength of the strongest one is used. Table 5.2 gives data on the tensile strength of some plastic types.

Table 5.2: Tensile strength of some plastic types [40]

Material	Ultimate Tensile Strength [MPa]
LDPE	20.7
HDPE	38
PP	41.4
PS	55.2
PVC	62

Before calculating the force required to cut down the plastic let, we determine the area under shear force.

$$\boldsymbol{A_{sh} = wt} \tag{1}$$

Where:

A_{sh} is an area under shear

w is the width of plastic under shear

t is the thickness of the plastic under shear

Assume the width of the plastic under shear at one blade jaw is $w = 4\,mm\ and$ the maximum thickness of the plastic waste if two plies of plastic are sheared together is $t = 2mm$.

Therefore, the area under shear will be

$$A_{sh} = wt = 4\,mmx2\,mm = 8\,mm^2$$

Assume factor of safety (FOS) = 3

The sheer force of polyvinyl (the hardest plastic material) is:

$$\boldsymbol{S_{us} = 0.577\,S_{ut}} \tag{2}$$

Where:

S_{us} is the ultimate tensile strength

S_{ut} is the ultimate shear strength

Then

If S_{ut} =62 MPa

$$S_{ut} = 0.577 \; x \; 62 \; MPa$$

$$S_{us} = 35.7 \; MPa$$

$$\boldsymbol{\tau = \frac{F_{sh}}{A_{sh}} = \frac{S_{us}}{FOS}} \tag{3}$$

Then,

$$F_{sh} = \frac{S_{us} \; x \; A_{sh}}{FOS} = \frac{35.7 \; MPax \; 8 \; mm^2}{3}$$

$$F_{sh} = 285.6 \; N$$

The cutting force (F_c)

If $S_y = 62 \; MPa$

$$\boldsymbol{\sigma = \frac{F_c}{A_c} = \frac{S_y}{FOS}} \tag{4}$$

$$F_c = \frac{S_y \; x \; A_c}{FOS} = \frac{S_y \; x \; A_c}{FOS}$$

Torque of shearing

$$\boldsymbol{T_{sh} = F_{sh} \; x \; R} \tag{5}$$

When $R = \; 300mm = 0.3 \; m$ is the radius of the rotor from the axis of the shaft up to the blade tip.

$T_{sh} = 285.6 \; MPa \; x \; 0.3 \; mm = 85.68 \; N - m$

Power required at the shaft

$$\boldsymbol{P = T_{sh}\ x\ W_{sh}} \qquad (6)$$

Assume $N_{sh} = 800\ rpm$

$$\boldsymbol{W_{sh} = \frac{2\ x\ \pi\ x\ N}{60}} \qquad (7)$$

$$W_{sh} = \frac{2\ x\ \pi\ x\ 800\ rpm}{60}$$

$$= 83.7\ \frac{rad}{s}$$

$$P = 7178\ W = 7.178\ kW = 9.6\ HP$$

Therefore, $\mathbf{10}\boldsymbol{HP}$ and above the power capacity of an electric motor is appropriate to run this rotor taking into consideration losses like friction and so on.

5.3. STRUCTURAL OPTIMIZATION

The problem of structural optimization can be categorized into three types: size, shape, and topology optimization (Figure 5.3). These classifications of optimization are integrated with the main design process (Figure 5.4).

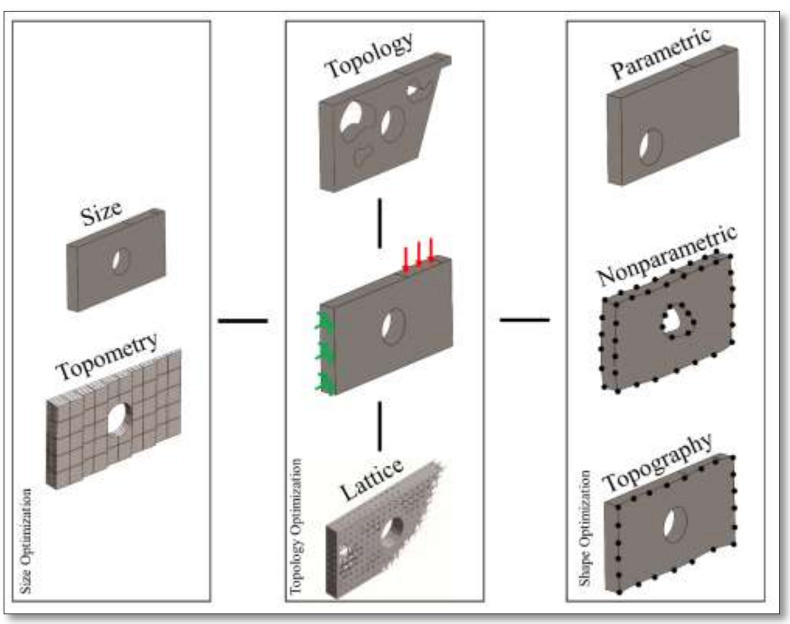


Figure 5.3: The types of optimization with simple hollow plate [41]

Size(parametric) optimization is the simplest form of structural optimization in which the shape of the structure is known and the objective is to optimize the structure by adjusting the sizes of the components. Here the design variables are the sizes of the structural elements, for example, the diameter of a rod or the thickness of a given model. *Shape optimization* is the optimization technique in which the general shapes of structures, including some features like holes, ribs, and other features are optimized. *Topology optimization* is an advanced structural design method that can obtain the optimal structure configuration via reasonable material distribution satisfying specified load conditions, performance, and constraints with either maximization or minimization objective function. Compared to sizing and shape optimization, topology optimization is independent of the initial configuration and has a broader design space. Topology optimization can be implemented through the use of finite element methods for the analysis and optimization techniques based on the Homogenization method, Optimality criteria method, level set, moving asymptotes, Genetic algorithms [42]–[46].

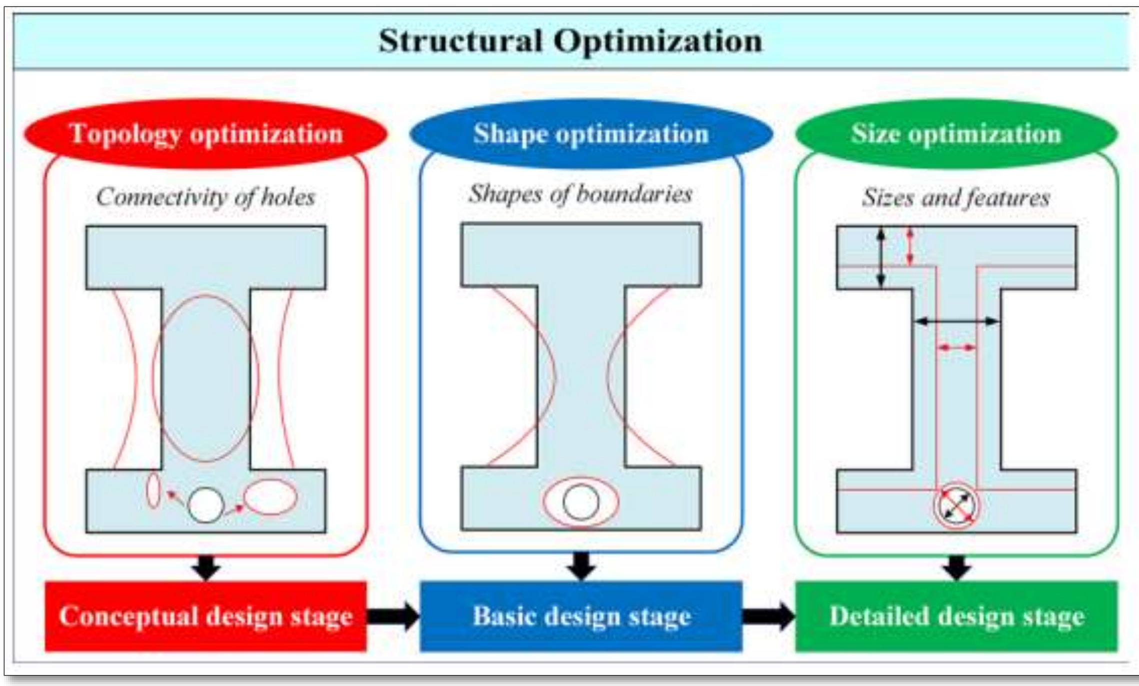


Figure 5.4: The integration of design process with the three types of optimization [47]*]*

5.4. OPTIMIZATION WITH ANSYS® PACKAGE

FE-based design optimization is currently a well-recognized and influential practice for engineering design. The application of this technique involves several stages such as geometric modeling, mesh generation, finite element method implementation, numerical optimization techniques, and some post-processing stages [48].

Ansys® started as a finite element software in 1970. The initial versions involved a command-based interface referred to as APDL (Ansys Parametric Design Language) which was the principal language used to communicate with the solver. The scripting language was used to build parametric models and automate common tasks. However, version 12 of the software drastically changed the interface by implementing a platform where projects are represented graphically as connected systems in a flowchart-like diagram known as Ansys Workbench™. The Ansys Workbench platform automatically forms connections between different types of studies and simulations. The desired study can be selected from an analyses menu and the study properties such as geometry, mesh, setup, solution, and results can be easily accessed or edited directly from the platform without the need of a script as in APDL [49].

Optimization was first implemented in an early version of Ansys APDL where a complete code needed to be developed which specified the system characteristics such as loads, dimensions, geometry, constraints, and other initial parameters. Once the model was outlined, the design variables and objective functions were defined along with the preferred optimization methods and techniques. The code was then run, and the outcomes highly depended on the convergence of the analysis [50].

With the release and enhancement of Ansys Workbench™ in version 12, users were allowed to create new, faster processes and efficiently interact with external tools such as CAD models. This improvement significantly increased the demand for finite element and optimization software in the engineering industry. Ansys version 2018 and later implements two fundamental types of optimizations which greatly simplifies the steps required to carry out an analysis. The first one is Topological Optimization: a form of shape improvement which is often referred to as layout optimization. Parametric Optimization is the second technique implemented. Parametric Optimization feature, which is contained within its module termed DesignXplorer™. Both the module is utilized in this work [49].

5.5. TOPOLOGY OPTIMIZATION MODULE

The topology optimization technology implemented in Ansys® Mechanical provides the necessary tools to design lightweight and efficient components for a wide range of applications.

The standard procedure for topology optimization involves defining the model and creating a mesh, specifying optimized and non-optimized regions, defining load cases and the optimization parameters (objective function/s and constraints).

In a general optimization problem statement, each finite element (i)generated in the meshing phase, is assigned a design variable (η_i) which is an internal, pseudo-density of the model. The pseudo-density ranges from 0 to 1, where $\eta_i = 0$ represents material to be removed and $\eta_i = 0$ represents material to be kept.

The topological optimization method can be also stated as follows:

$minimize/maximize\ f(\eta_i)$

Subject to:

$$0 \leq \eta_I \leq 1 \qquad (I = 1,2,3, \ldots, N)$$

$$\overline{g_J} \leq g_J \leq \overline{\overline{g_J}} \qquad (J = 1,2,3, \ldots, M)$$

Where:

N = $number\ of\ finite\ elements$

$M = number\ of\ constraints$

$g_J = computed\ constraint\ value$

$\overline{g_J}$ and $\overline{\overline{g_J}}$ $=lower\ and\ upper\ constraint\ bounds$

The procedure of topology optimization is presented in Figure 5.5.

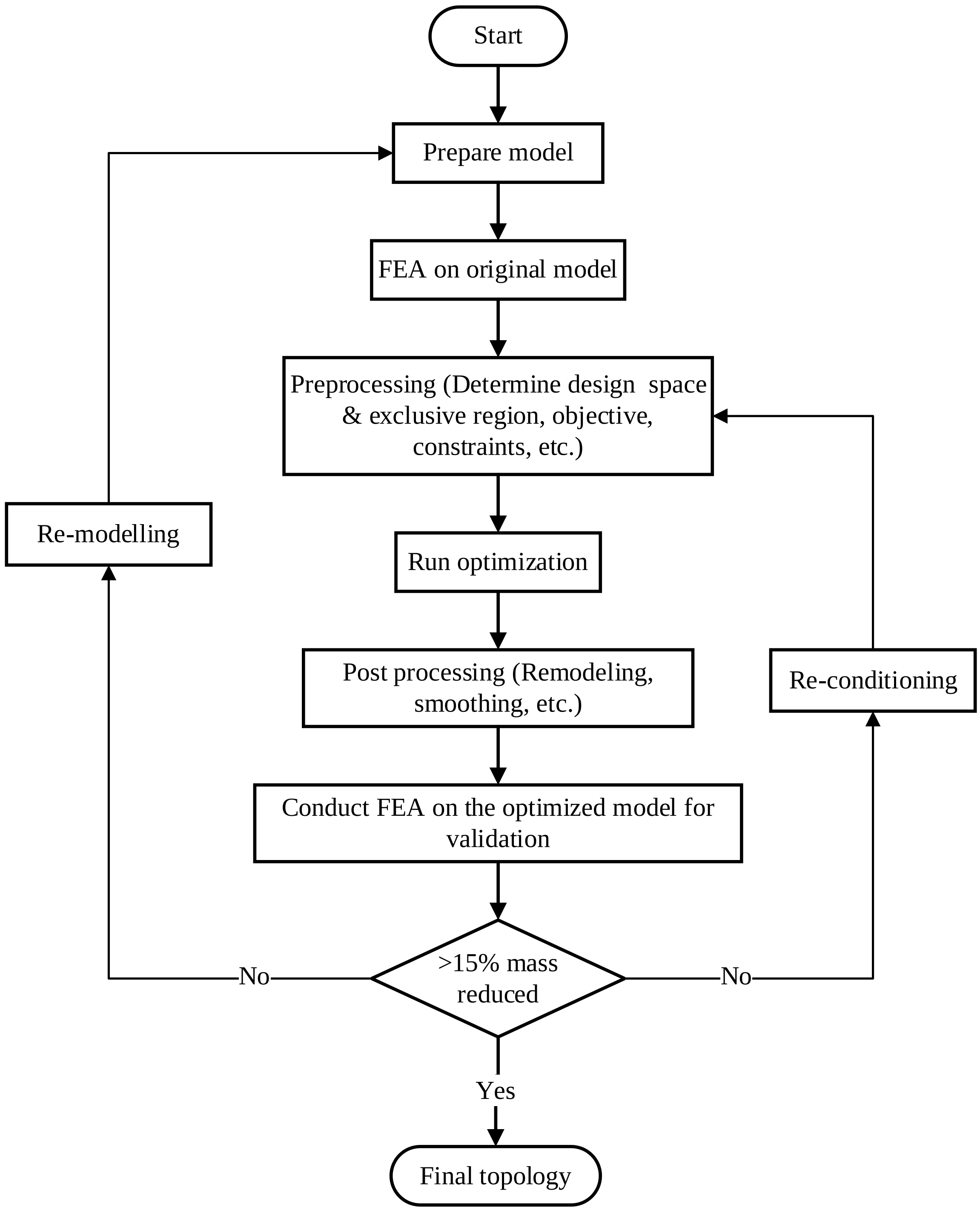


Figure 5.5: The process of topology optimization

5.6. DESIGN EXPLORATION MODULE

The main purpose of the *Design Exploration Module* is to effectively identify the relationship between the design variables and the desired performance of a model. Based on the output, the analyst can modify and influence the design, so the required outcomes are obtained. *Design Exploration Module* provides enough tools to perform parametric optimization cases with a reasonable number of parameters in a single or Multiphysics analysis. In other words, *Design Exploration Module* is a powerful approach to explore, understand, and optimize an engineering challenge. The *Design Exploration Module* is one of the most advanced optimization tools available and is widely used in the engineering industry as well as in a variety of research fields. It includes as part of the response surface, goal-driven optimization, and other analysis systems.

Design Exploration Module provides the following types of optimization algorithms:

- *Shifted Hammersley Sampling:* An optimization method used for sampling generation in the analysis. The Shifted Hammersley algorithm is a quasi-random number creator generally used for Quasi-Monte Carlo analyses (numerical integration simulations) where the algorithm provides low-discrepancy sequences (samples)
- *Multi-Objective Genetic Algorithm (MOGA):* The MOGA is a development of the NSGA-II (Non-dominated Sorted Genetic Algorithm) which is a type of Evolutionary algorithm. The main purpose of the algorithm is to augment the adaptive fit of a population of potential solutions to a Pareto front constrained by a set of specified objective functions. The technique implements an evolutionary procedure with selection, genetic crossover, and mutation operators. The typical steps involved in a MOGA analysis include the incorporation of an initial population from the defined parameters. Then, MOGA creates a new population via Crossover and Mutation, and the design points in the new population are updated. Consequently, a convergence validation is carried out, if the optimization converged, the analysis is ended, and the results are generated. However, if the study did not converge, a stopping criteria validation is conducted. Depending on whether the maximum number of iterations set was reached, the analysis can be finished without iteration of the algorithm is run again generating a new population if the maximum number of iterations set was not reached.

- *Nonlinear Programming by Quadratic Lagrangian*: The NLPQL method is a numerical optimization algorithm. This technique is specially developed to solve constrained non-linear programming models. In principle, the method generates a sequence of subproblems obtained from a quadratic approximation of the Lagrangian function and linearization of constraints. Consequently, the information is updated by an iterative Newton's method and finally stabilized by a line search. The method assumes the problem size is relatively small-scale and the accuracy largely depends on numerical gradients obtained.
- *Adaptive Single and Multi-Objective Optimization:* ASO is a mathematical optimization technique that implements the MOGA optimization algorithm supporting single or multiple objectives, multiple constraints, and limited to continuous parameters.

5.6.1. Elements of Design Exploration module

Design exploration includes several systems, like 3D ROM, Direct Optimization, Parameters Correlation, Response Surface, Response Surface Optimization, and Six Sigma Analysis (Figure 5.3).

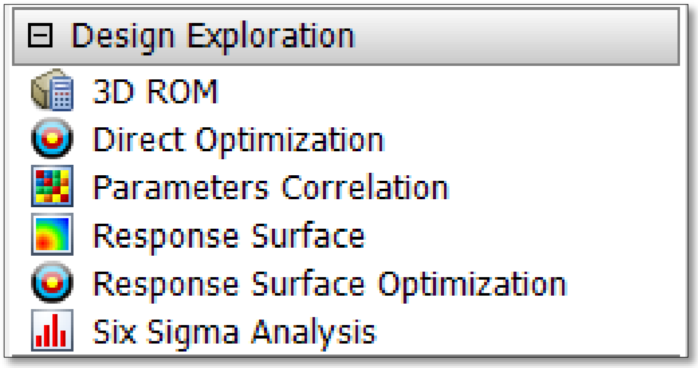


Figure 5.6: Elements of design exploration

5.7. TOPOLOGY OPTIMIZATION OF BLADE CARRIAGE

The procedure followed to do topology optimization is summarized on Figure 5.6.

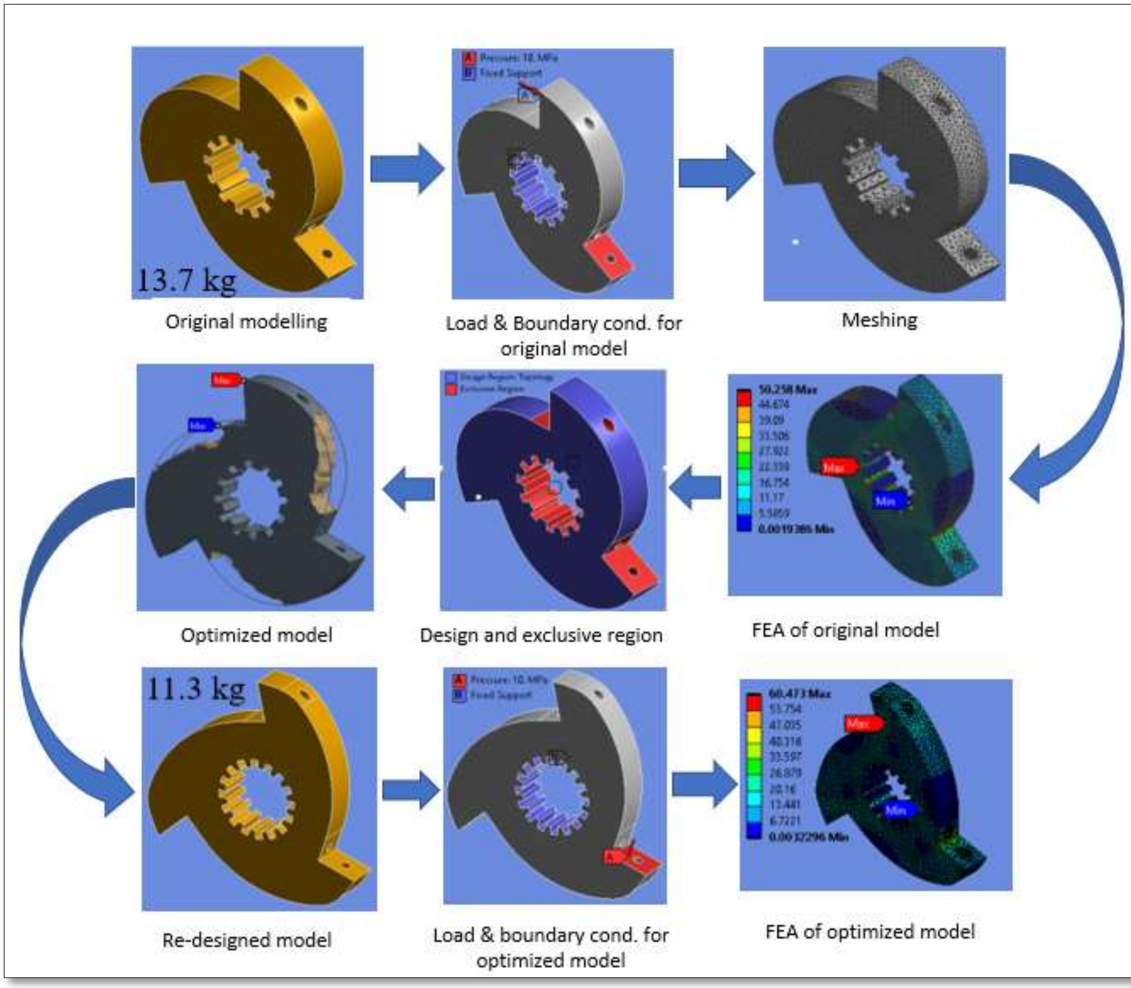


Figure 5.7: The general workflow of topology optimization

Here below the procedure for the topology optimization is given.

1. Static structural analysis on the original model

Dragging static structural from the analysis systems column into the project schematic region.

The CAD model of the geometry of blade carriage is created in *SolidWorks®V20R1* and directly imported to *the Ansys19®V19R3* workbench (Figure 5.8).

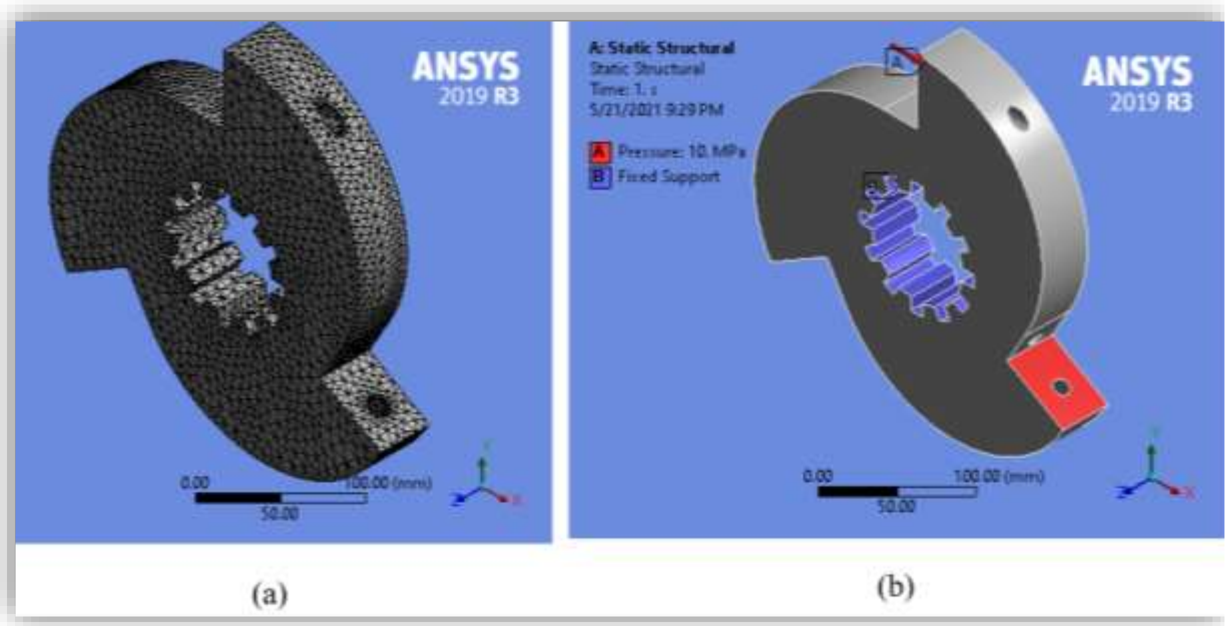


Figure 5.8: Pre-processing setup (a) Meshing (b) Boundary condition

In the meshing process, the meshing size and the defeature size are set to 5 mm, and the span angle center is set to fine meshing (Figure 5.8 (a)). The boundary condition and the load applied on the carriage are as shown in Figure 5.8 (b). The spline hub of the carriage is set fixed boundary condition and the pressure of 10 MPa is applied to the three jaws. In the practical condition even if the three-jaw is not loaded at the same time however the loading condition is the same, that is why the same amount of load and loading condition is used. The result of this analysis is presented in Section 6.1.

2. Topology optimization (TO)

First of all, the topology optimization module is dragged and dropped (with the linkage to the static analysis) from the analysis system to the project schematic. Engineering data, geometry, and model tabs are directly joined. To simplify the process static results are linked to topology optimization set up to simplify the process. Then double click the setup to load into Ansys mechanical. After connecting geometry, static structural and topology optimization the schematic looks like Figure 5.9. The outline of Ansys mechanical looks as it is in Figure 5.10.

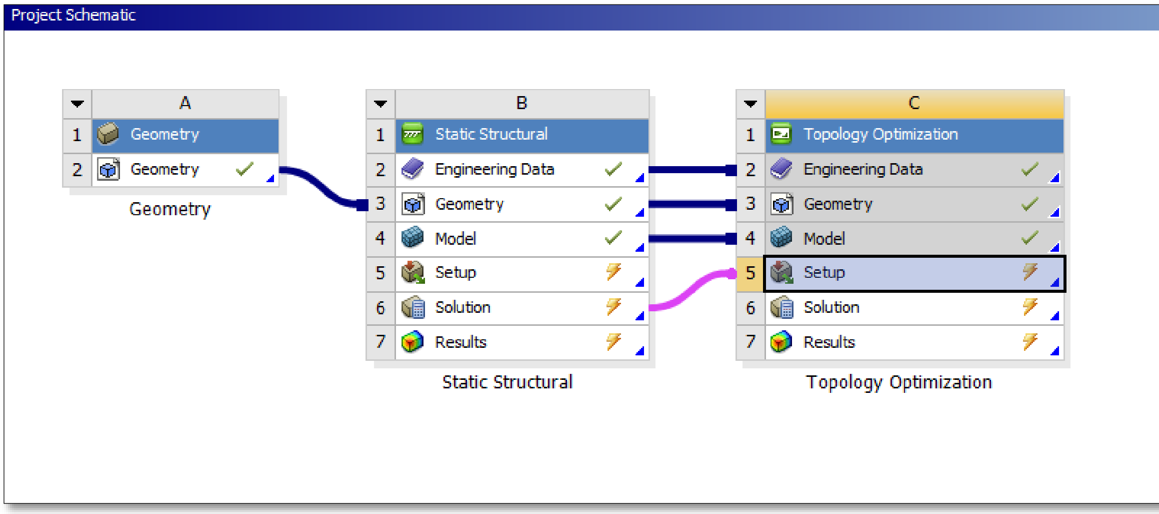


Figure 5.9: Static structural boundary condition

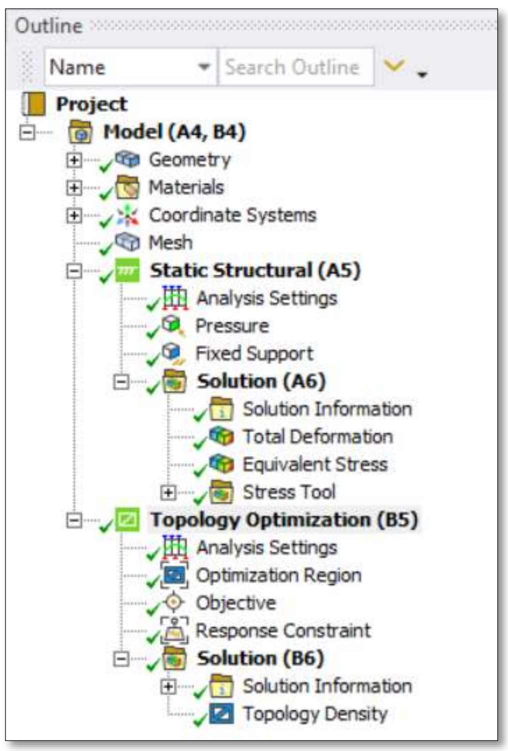


Figure 5.10: Ansys mechanical topology optimization outline

Under analysis settings, as is shown in Figure 5.11 a maximum number of iterations is (500), convergence accuracy is (0.1%) and the type of solver will be defined by the solver.

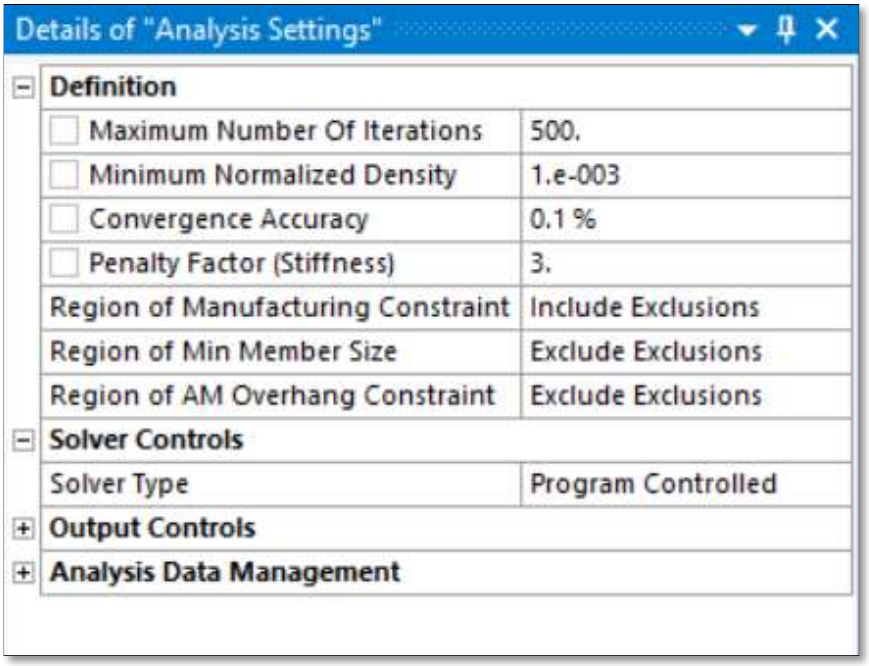


Figure 5.11: The analysis setting

Under the topology optimization tab, the optimization region is selected, and then, under geometry in the design region, all bodies are selected. In the exclusion region, is the surface that is not subjected to optimization: these surfaces are the screw ways, the surface was the blade is placed and the fixed boundary condition (Figure 5.12).

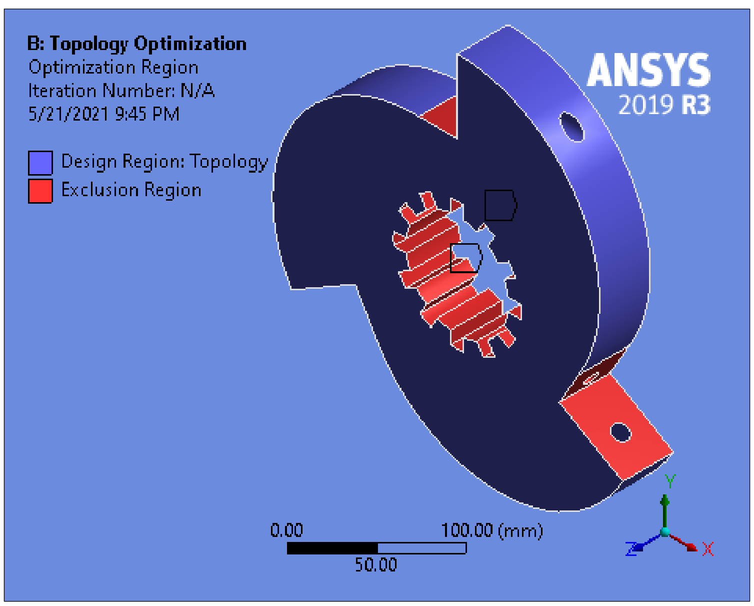
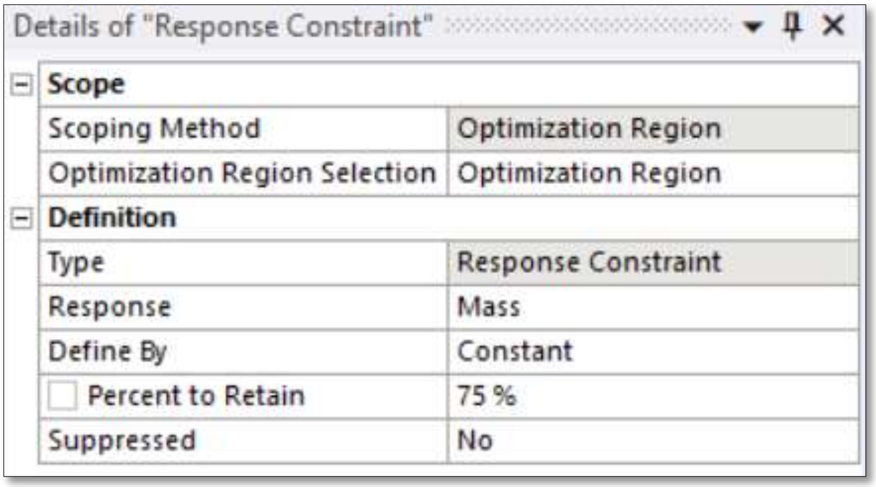


Figure 5.12: The design and non-design region

The objective of the optimization is to minimize the mass of the member by 25% (75% retained) (Figure 5.13).


Details of "Response Constraint"

Scope	
Scoping Method	Optimization Region
Optimization Region Selection	Optimization Region
Definition	
Type	Response Constraint
Response	Mass
Define By	Constant
Percent to Retain	75 %
Suppressed	No

Figure 5.13: The objective and constraints of the optimization

3. Static structural analysis on optimized model

For validation the model is modified on SOLIDWORKS, it is exported back to ANSYS for a new static structural analysis. The analysis result of the modified carriage is given on Appendix-A details all the parameters of the component that is drawn on the SOLIDWORKS drawing template before parametric optimization.

5.8. PARAMETRIC OPTIMIZATION OF THE SPLINED BLADE CARRIAGE

Parametric optimization deals with the search for the best possible design solution according to the objectives under consideration of the predefined constraints. The mathematical definition of the optimization problem can be outlined as;

$min\ (f(x))$

subjected to: $g_j(x) \leq 0 \qquad j = 1 \ldots m_g$

$h_k(x) = 0 \qquad k = 1 \ldots m_k$

$x_{i,min} \leq x \leq x_{i,max} \qquad i = 1 \ldots n$

where $f(x)$ represents the objective function and x is the vector of design variables within the predefined permissible range. The functions $g_j(x)$, $h_k(x)$ and x are the inequality, equality and constantly bounded constraints respectively [51].

In the Ansys workbench package, the procedure of parametric optimization is:

- Launching Ansys®V19R3 workbench
- Opening static structural analysis
- Importing solid work part directly
- Setting parameter on design modeler
- Opening setup, and apply load and boundary condition
- Running the static structural analysis
- Checking the parameter for the result
- Updating design experiment
- Connecting response surface to parameter set and update
- Connecting response surface optimization to response surface and parameter set and update
- Connecting six sigma analyses to parameter set update
- Fetching result
- Exporting the optimized model to a new geometry

In a simplified way parametric optimization in design exploration is represented by pre-processing, simulation, post-processing, and archive (Figure 5.14). In this process, we may use

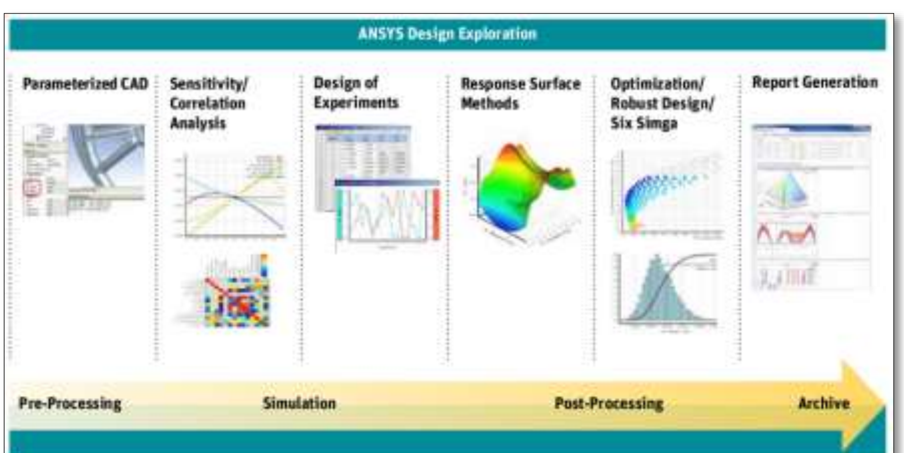


Figure 5.14: The process of parametric optimization in design exploration

some or all the systems found under design exploration depending on the types of problems to be handled.

5.9. PARAMETRIC PROBLEM EXPRESSION OF THE SPLINED BLADE CARRIAGE

The geometry that is used in this parametric optimization is the geometry gotten from topology optimization. The geometry with five important input parameters (P1, P2, P4, P5, and P6) is given in Figure 5.15. Descriptions of those parameters and the lower bound and upper bound of the parameters are given in Table 5.3. The main aim of the parametric optimization is to find the input parameters which minimize the total deformation and von-mises stress and maximize the factor of safety of the member.

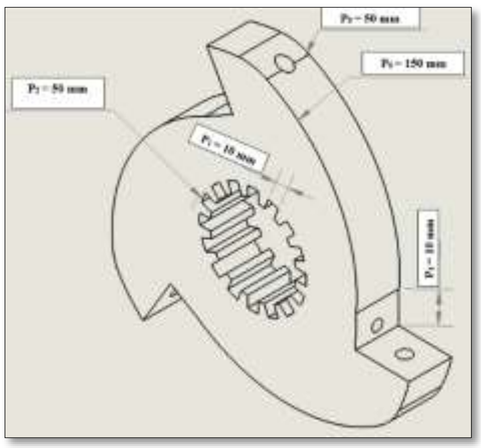


Figure 5.15: The five input parameters

Table 5.3: The parameters with lower and upper bound

	Parameter	Lower bound	Upper bound
P1	The thickness of the spline way	9 mm	11 mm
P2	The outer radius of the spline	45 mm	55 mm
P4	Back blade retainer	27 mm	33 mm
P5	Corner fillet radius	45 mm	55 mm
P6	The back radius of the carriage	135 mm	165mm

As it is shown in Figure 5.16 the input parameters of this optimization are five namely 1) thickness of spline way 2) outer radius of spline 3) back blade retainer 4) corner fillet radius 5) back radius of carriage; and the output parameters are three: 1) total deformation maximum 2) equivalent stress maximum 3) safety factor minimum.

Outline of All Parameters

	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	Input Parameters			
3	Static Structural (A1)			
4	P1	Thickness of spline way	10	
5	P2	Outer radius of spline	50	
6	P4	Back blade retainer	30	
7	P5	Corner fillet radius	50	
8	P6	Back radius of carriage	150	
*	New input parameter	New name	New expression	
10	Output Parameters			
11	Static Structural (A1)			
12	P7	Total Deformation Maximum	0.072815	mm
13	P8	Equivalent Stress Maximum	142.06	MPa
14	P9	Safety Factor Minimum	1.7598	
*	New output parameter		New expression	
16	Charts			

Figure 5.16: The input and output parameters in optimization

Before going to parametric optimization static structural analysis of the topology optimized model should carried out. Then the output parameters should be parametrized. When the parametrization of input and output parameters in Solidwork and Ansys are properly parametrized respectively the integration of Ansys project workspace looks like the one on (Figure 5.17). After parametrization, all the design exploration systems should be dragged to the workspace one by one.

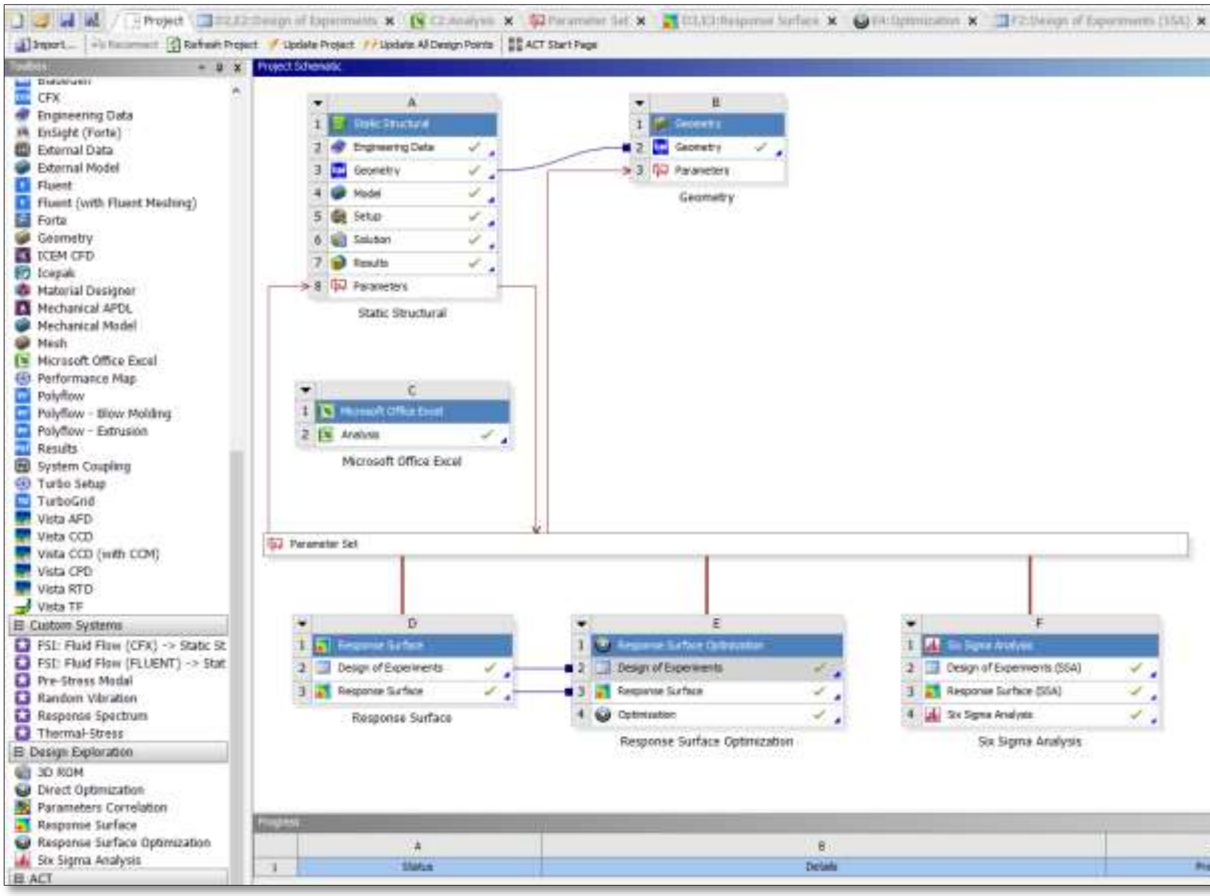


Figure 5.17: Ansys Workbench set-up for response surface optimization and six sigma analysis

5.10. DESIGN OF EXPERIMENT (DOE)

DOE is a generic statistical method that guides the design and analysis of experiments to find the cause-and-effect relationship between "factors" (inputs) and "response" (output). It was initially developed to study agricultural experiments in the 1930s. Later the first industrial applications of DOE were in the British textile industry [52].

In the topology optimization module of Ansys, DOE is used to generate the input and output parameters for each design point where the virtual experiment can be carried out. The input parameters are constrained between lower and upper bound and design points are the points where the optimization objectives are analyzed and compared. The design points may vary depending on the number of input and output parameters.

In this work the DOE of blade carriage parametric optimization is given on (Table 5.4), where 27 design points are generated. For example, in design point, no.10 Ansys calculates the total deformation, von-Mises stress, and safety factor by considering all the input parameters at that point. Then it compares the result of all the design points and proposes the best candidate which minimizes the deformation and stress, and maximizes the factor of safety.

Table 5.4: DOE for 27 design points

Design point	P_1	P_2	P_4	P_5	P_6	P_7	P_8	P_9
1	10	50	30	50	150	0.072815	142.06	1.7598
2	9	50	30	50	150	0.074674	142.19	1.7582
3	11	50	30	50	150	0.074402	163.49	1.5292
4	10	50	30	50	150	0.080793	158.83	1.574
5	10	50	30	50	150	0.069475	156.05	1.6021
6	10	50	27	50	150	0.074282	153.9	1.6245
7	10	50	33	50	150	0.07475	157.58	1.5865
8	10	50	30	45	135	0.074247	148.29	1.6859
9	10	50	30	55	165	0.074716	153.97	1.6237
10	10	50	30	50	154.25	0.075665	139.55	1.7915
11	10	50	30	50	145.75	0.072945	141.64	1.7651
12	9.7167	48.583	29.15	48.58	145.75	0.075454	158.54	1.5769
13	10.283	48.583	29.15	48.58	154.25	0.076367	162.56	1.5379
14	9.7167	51.417	29.15	48.58	145.75	0.073489	147.52	1.6947
15	10.283	51.417	29.15	48.58	145.75	0.072609	154.87	1.6143
16	9.7167	48.583	30.85	48.58	154.25	0.076442	149.29	1.6746
17	10.283	48.583	30.85	48.58	145.75	0.075728	162.88	1.5349
18	9.7167	51.417	30.85	48.58	145.75	0.072838	148.25	1.6864
19	10.283	51.417	30.85	51.42	154.25	0.073409	151.37	1.6515
20	9.7167	48.583	29.15	51.42	145.75	0.076271	151.55	1.6497
21	10.283	48.583	29.15	51.42	145.75	0.075589	152.34	1.641
22	9.7167	51.417	29.15	51.42	154.25	0.072529	150.29	1.6634
23	10.283	51.417	29.15	51.42	145.75	0.073496	150.52	1.6609
24	9.7167	48.583	30.85	51.42	145.75	0.075771	143.37	1.7437
25	10.283	48.583	30.85	51.42	154.25	0.076498	145.58	1.7173
26	9.7167	51.417	30.85	51.42	145.75	0.073657	144.63	1.7285
27	10.283	51.417	30.85	51.42	145.75	0.072976	144.7	1.7277

The optimization schematic outline is divided into three parts: objectives and constraints, domain, and results. As its discussed in a Section 5.9 there are three objectives in this parametric optimization: deformation, stress and FOS. The constraints of these objectives are presented on Figure 5.18. Thus, the deformation ($P_7 \leq 0.071$ mm), stress ($P_8 \leq 141\ Mpa$) and the FOS ($P_9 \geq 1.8$). In the domain all the input parameters can be checked from the square box at the front of each of parameters. The results that can be extracted from this schematic outline are candidate points, tradeoff, samples and global sensitivity. These results are presented and discussed in Section 6.2.2.

CHAPTER SIX

6. RESULT AND DISCUSSION

This chapter presents all the result that are extracted from Ansys Workbench and discusses all of them one by one. These results are the result from topology optimization and the results from parametric optimization.

6.1. RESULTS OF TOPOLOGY OPTIMIZATION OF BLADE CARRIAGE

As it is seen in the figure below (Figure 6.1) the original model mass (Figure 6.1(a)) is 13.7 Kg. After topology optimization, it is minimized by 25 % (75% retained) and it will come to 10.3 Kg. However, the optimized model (Figure 6.1(b)) has an irregular shape which makes it difficult for manufacturing. Due to this reason smoothing the shape and giving determined parameters is necessary. Accordingly, the optimized model is smoothed and modified. The mass of the member is little bit increased to 82.3% from 75% of the original one. Finally, the modified model (Figure 6.1(c)) mass becomes 11.3 Kg.

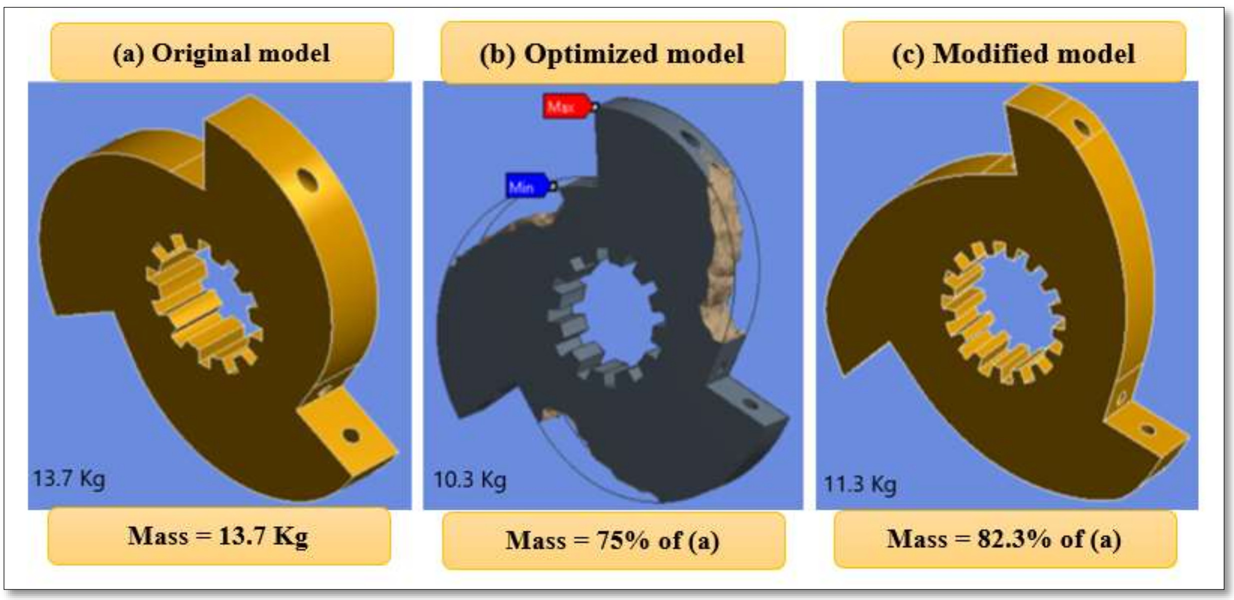
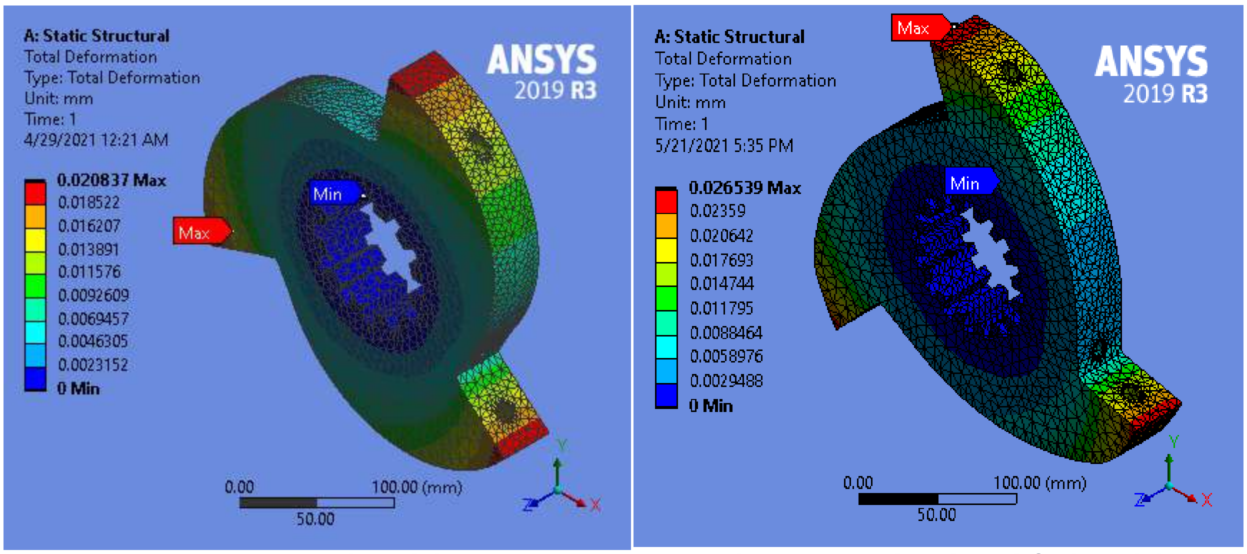


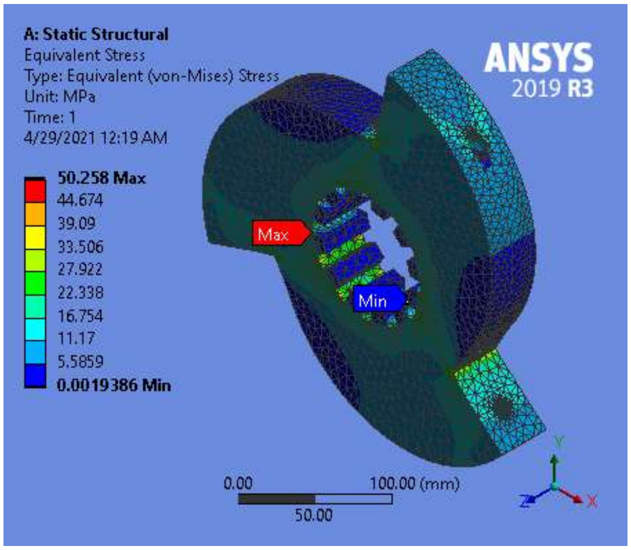
Figure 6.1: The mass of the models (a) Original model (b) Optimized model (c) Modified model

For validation, the comparative study on static structural analysis of the original and optimized model was taken. Thus, Figures 6.2, 6.3, and 6.4 presented the total deformation, von-mises stress, and factor of safety respectively. As one can see from the result found, the deformation is increased from 0.020 mm to 0.026 mm and the von-mises stress is also increased from 50.25 MPa to 60.47 MPa. Nevertheless, the result of the deformation and von-mises stress shows increment, still, the component is much more below the yield point. This can be seen from Figure 6.4, in which the factor of safety of the original and optimized model is presented. The factor of safety of the original model is 4.9 and the optimized one is 4.1. Even if the result is increased the component is still in the safe zone.

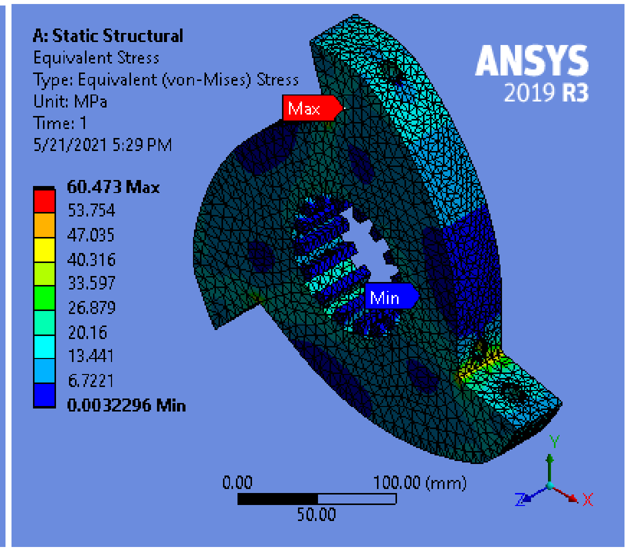


(a) Original model *(b) Optimized and modified model*

Figure 6.2: Total deformation

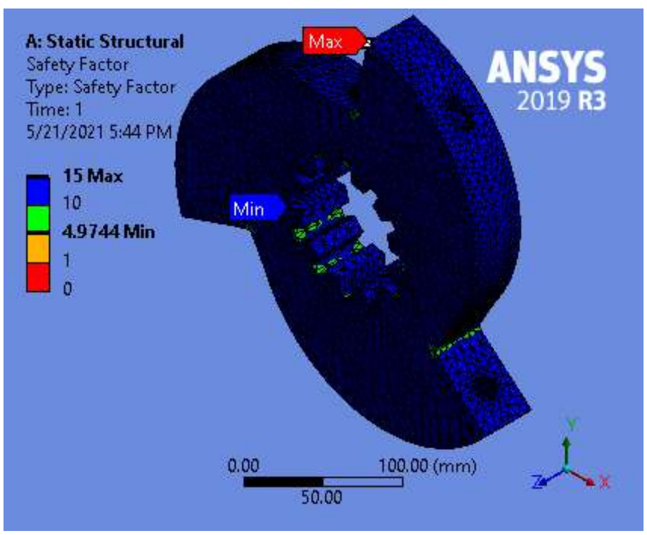


(a) Original model

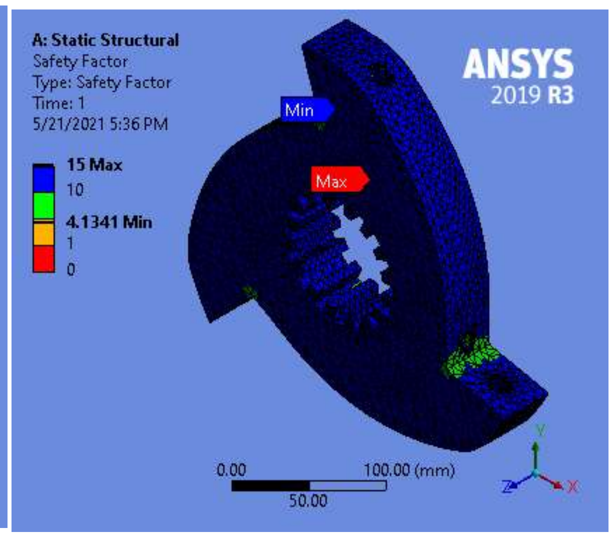


(b) Optimized and modified model

Figure 6.3: Von-Mises stress



(a) Original model



(b) Optimized and modified model

Figure 6.4: Factor of Safety

6.2. RESULTS OF PARAMETRIC OPTIMIZATION

In this topic the results of parametric optimization are presented and discussed. The topic is divided into three sub-topic which are Response Surface (Section 6.2.1), Response Surface Optimization (Section 6.2.2) and Six-sigma Analysis (Section 6.2.3).

6.2.1. Response Surface

Parameters parallel chart (Figure 6.5) generates a graphical display of all the 27 design points with lower bounds and upper bounds of input and output.

The graph of *design points vs parameters* shows and analyzes each design point with output parameters. For example, in (Figure 6.6) the maximum deformation of blade carriage occurs at the 4th design point and the minimum occurs at the 5th design point. In the same manner, the maximum von-mises stress and minimum von-mises stress occur at the 2nd design point and 3rd design point respectively (Figure 6.7). The same thing applies to the factor of safety (Figure 6.8).

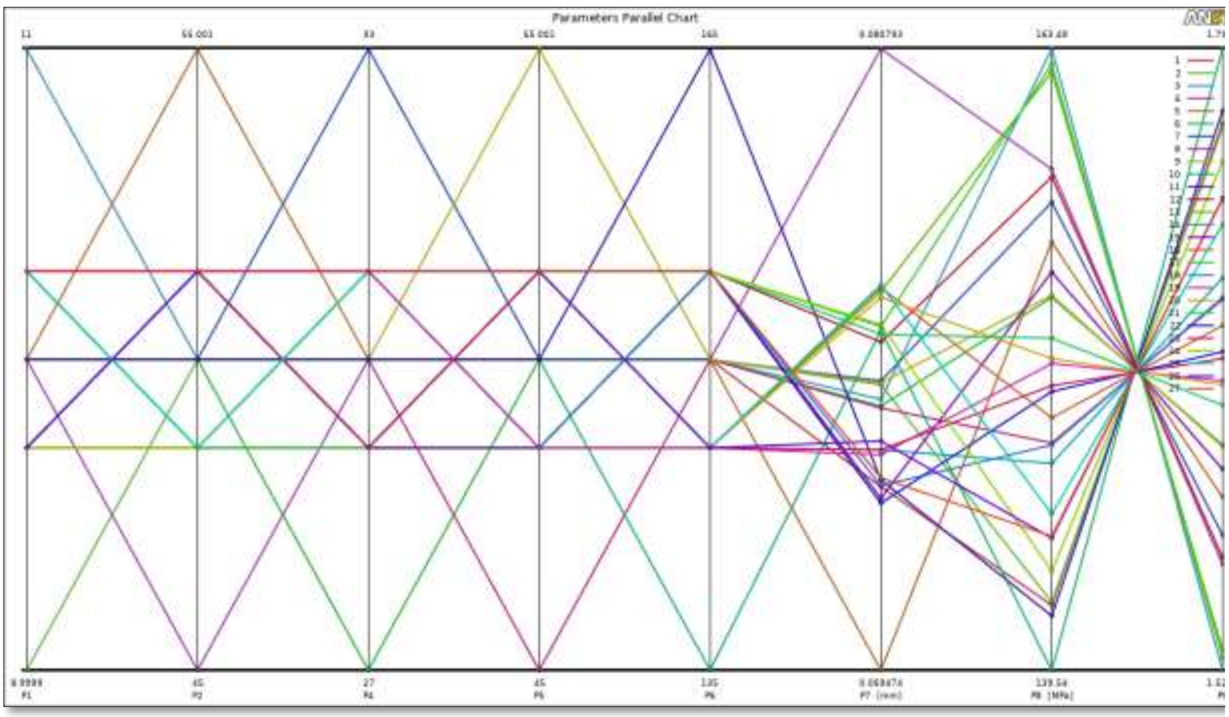


Figure 6.5: Parameters parallel chart

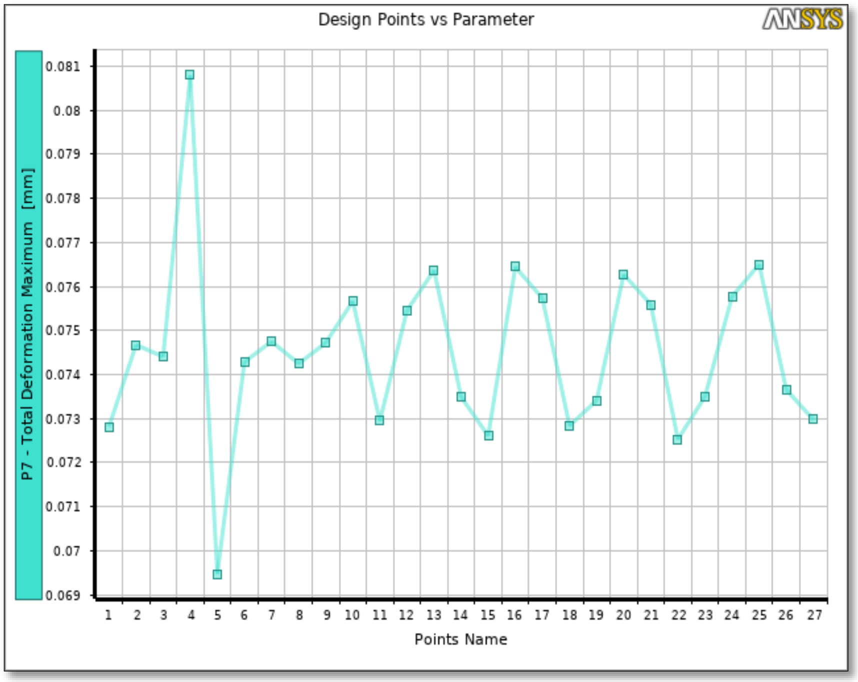


Figure 6.6: Design points vs Max. total deformation

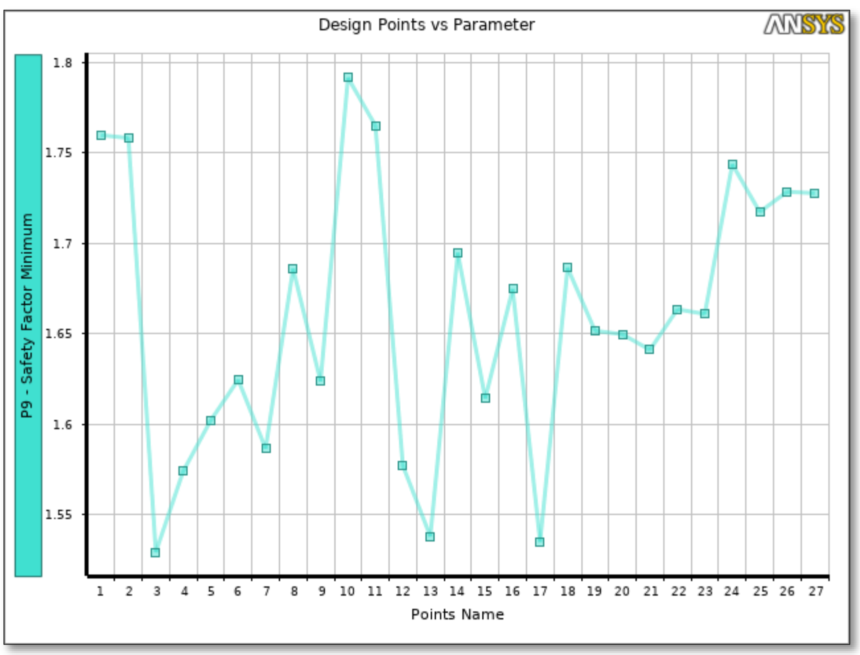


Figure 6.7: Design points vs Min. safety factor

The ***local sensitivity chart*** allows seeing the weight of the different inputs for each output. This chart calculates the change of the output based on the change of each input independently, at the current value of each input parameter in the project. It can be displayed as a bar chart or pie chart. In the case of this work, the Local sensitivity chart of the output parameter is presented by bar chart (Figure 6.9). For example, as it is seen from this figure the total deformation maximum is more sensitive to an outer radius of spline whereas equivalent stress maximum and safety factor minimum are more sensitive to the thickness of spline way than other input parameters.

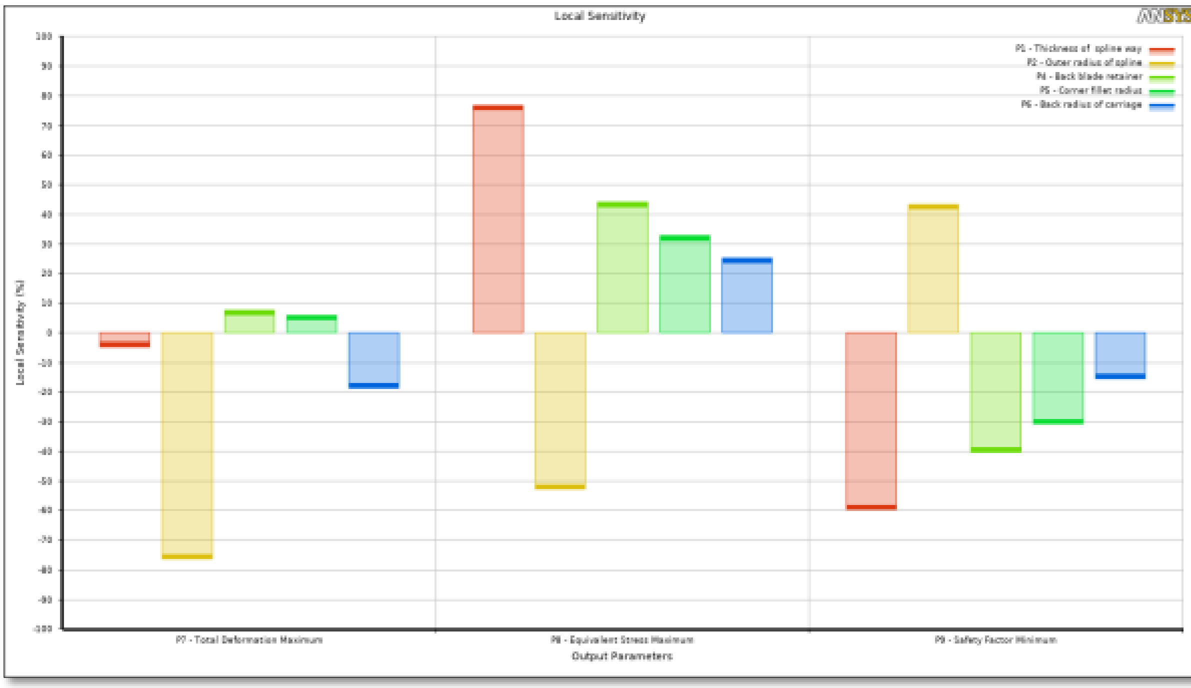
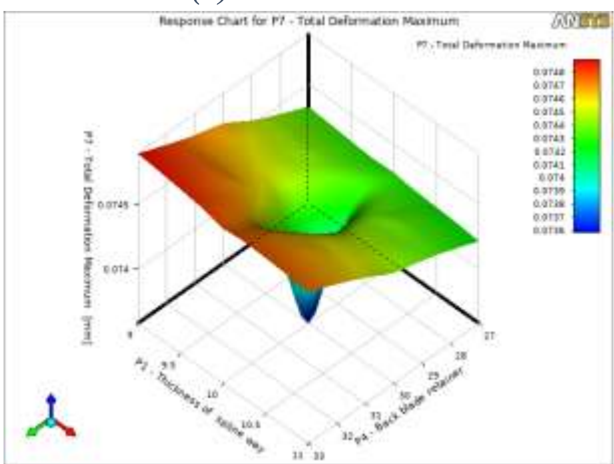


Figure 6.8: Local sensitivity of the output to the input parameters

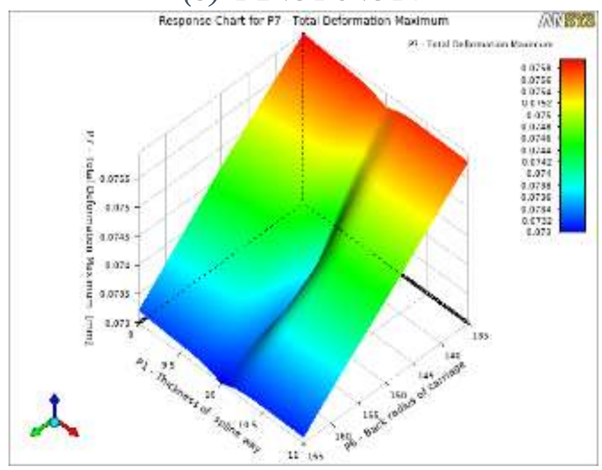
Response surfaces are functions of varying natures in which the output parameters are described in terms of the input parameters. Built from the DOE, they quickly provide the approximated values of the output parameters throughout the design space without having to perform a complete solution. Once a response surface is generated, it is possible to create and manage response points and charts. These postprocessing tools help you to understand how each output parameter is driven by input parameters and how you can modify your design to improve its performance.

Response surface include full second-order polynomial, kriging, non-parametric regression, and neural network approaches. These serve to interpolate between the data points in multi-dimensional space. They can be visualized as a 2-D or 3-D description of the relationships between design variables and design performance. But, here the 3-D description is presented (Figure 6.10). For example, in Figure 6.10 (a) he response of total deformation with thickness of spline way and back blade retainer is shown. In this graph the minimum deformation is encountered at (P1=10 mm and P4= 30 mm) and the maximum deformation is at (P_1= 9 and P_4= 30). The same interpretation applies for all graphs.

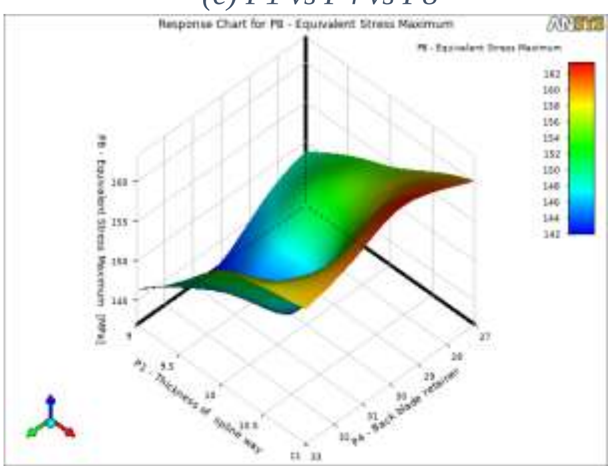
(a) P1 vs P4 vs P7



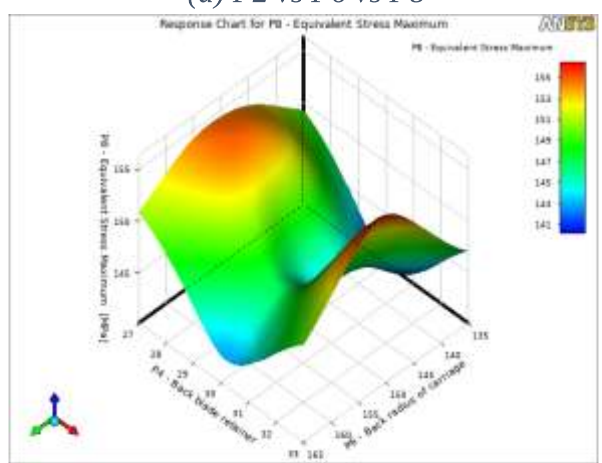
(b) P1 vs P6 vs P7



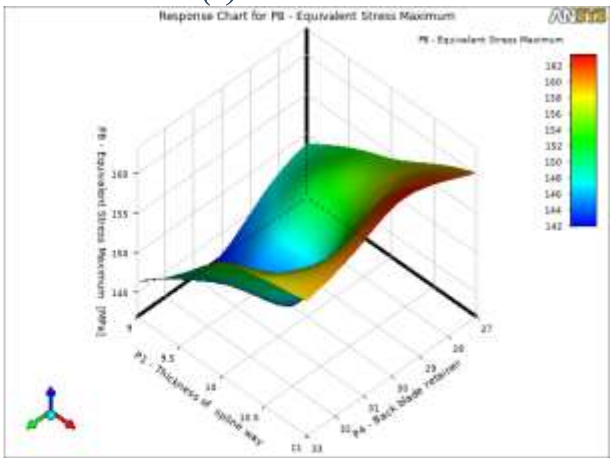
(c) P1 vs P4 vs P8



(d) P2 vs P6 vs P8



(e) P1 vs P5 vs P9



(f) P2 vs P6 vs P9

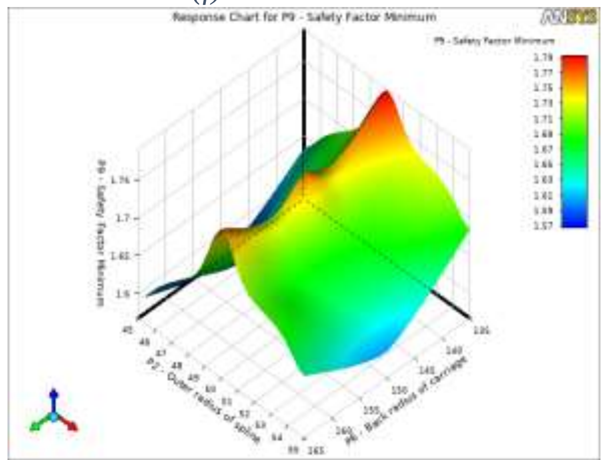


Figure 6.9: Response surface

Local Sensitivity Curves (LSC) helps to further focus on the analysis by allowing to view independent parameter variations within the standard local sensitivity curves. It provides a means of viewing the effect of each input on specific output, given the current values of other parameters. Local sensitivity chart presents the effects of input parameter by negative and positive values without output value whereas, the local sensitivity curve presents with the exact values of the output value.

On Figure 6.11 the local sensitivity curve of deformation is presented. As it is seen from the figure deformation is more sensitive to outer radius of the blade carriage negatively. The second more sensitive parameter is back radius of the component positively. The least sensitive one is the back radius.

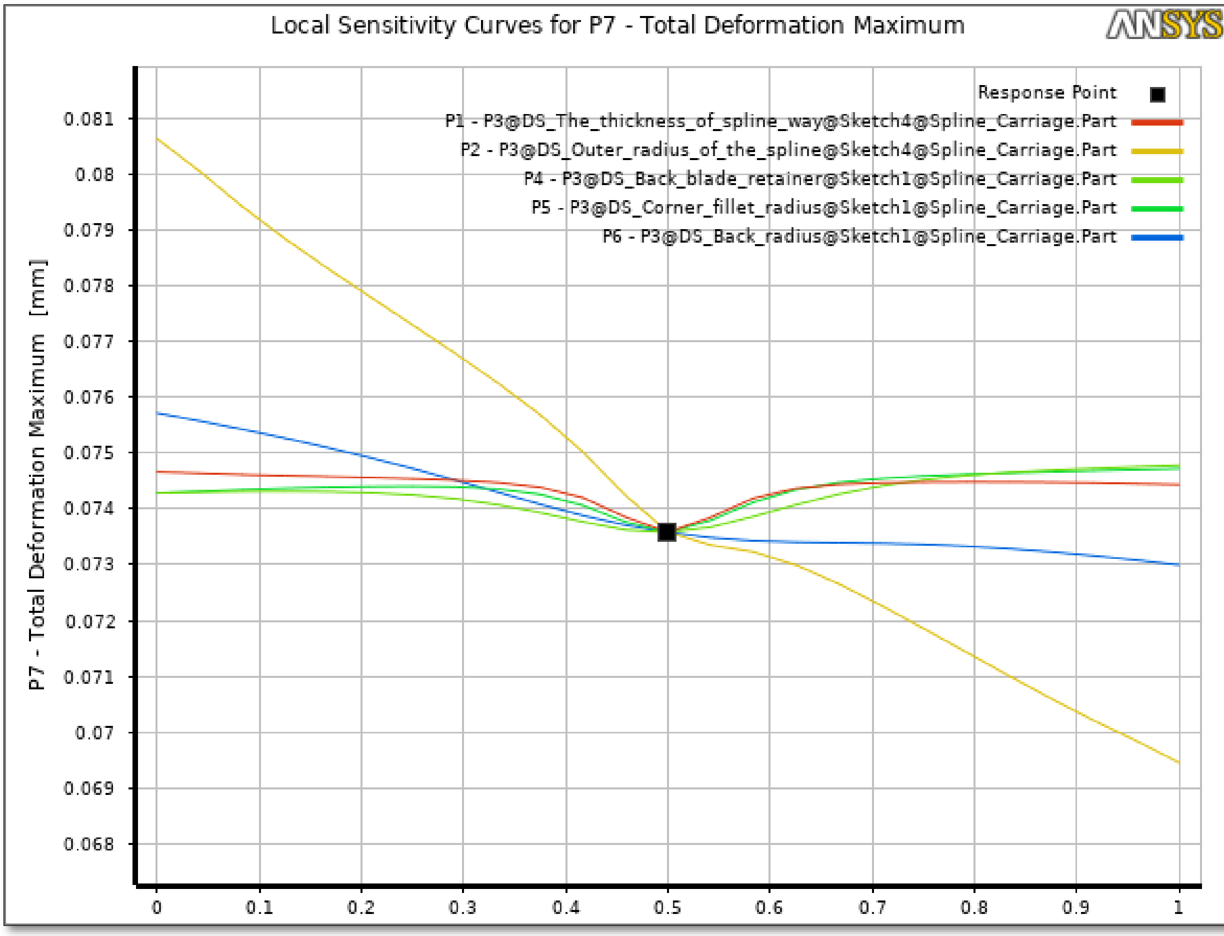


Figure 6.10: Local sensitivity curves of deformation

In the same manner Figure 6.12 presents local sensitivity curve of equivalent stress maximum. As it is shown on the figure the equivalent stress maximum is positively more sensitive to the thickness of spline way and less sensitive to back radius of blade carriage.

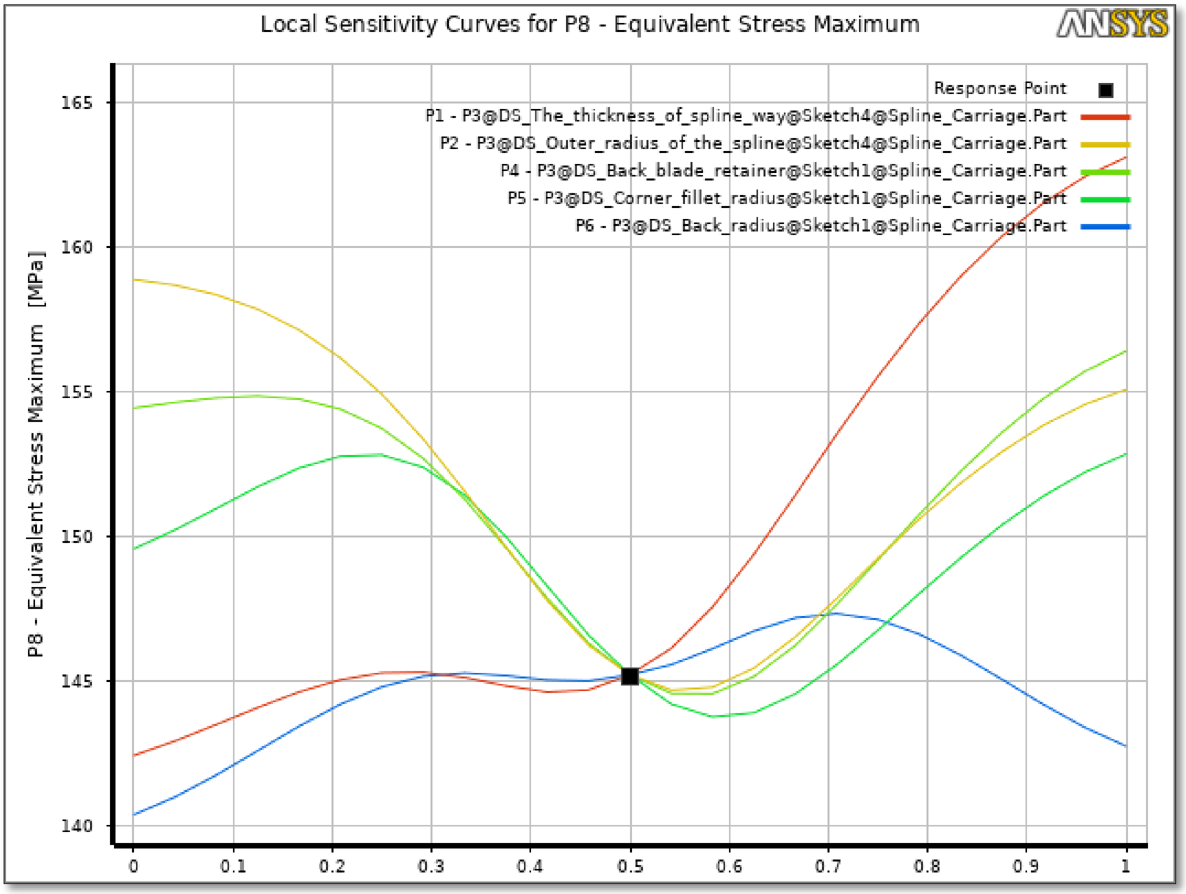


Figure 6.11: Local sensitivity curves of equivalent stress

Likewise, thickness of spline way has a higher negative sensitivity effect and the back radius also has negative sensitivity effect on the safety factor minimum.

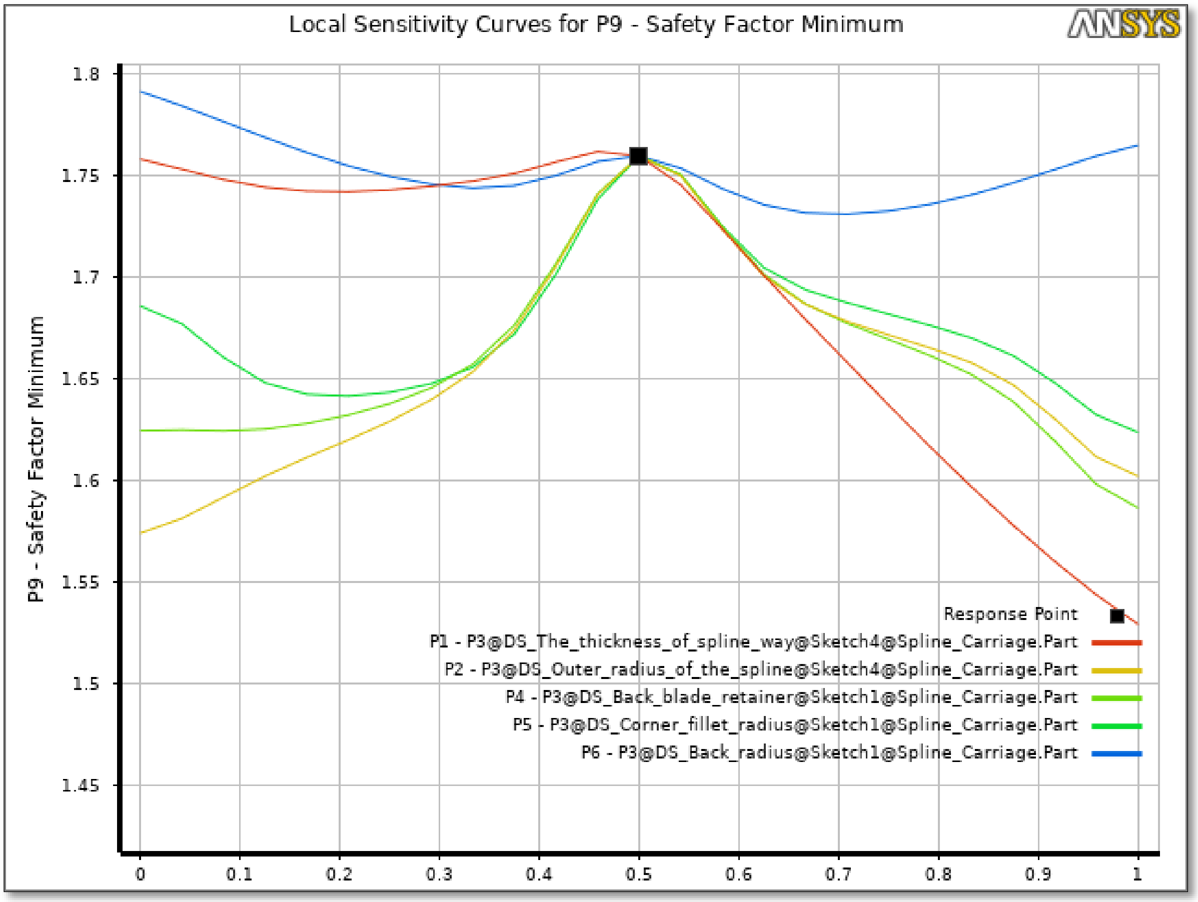


Figure 6.12: LSC for safety factor minimum

The goodness of fit chart (Predicted vs Observed chart) shows the values predicted from the response surface versus the values observed from the design points. This scatter chart enables to quickly determine if the response surface correctly fits the points of the design points table and refinement table. The closer the points are to the diagonal line, the better the response surface fits the points (Figure 6.14).

By default, all output parameters are displayed on the chart, and the output values are normalized. However, if only one output parameter is plotted, the output values are not normalized. Verification points are not used in the generation of the response surface. Consequently, if they appear close to the diagonal line, the response surface is correctly representing the parametric model.

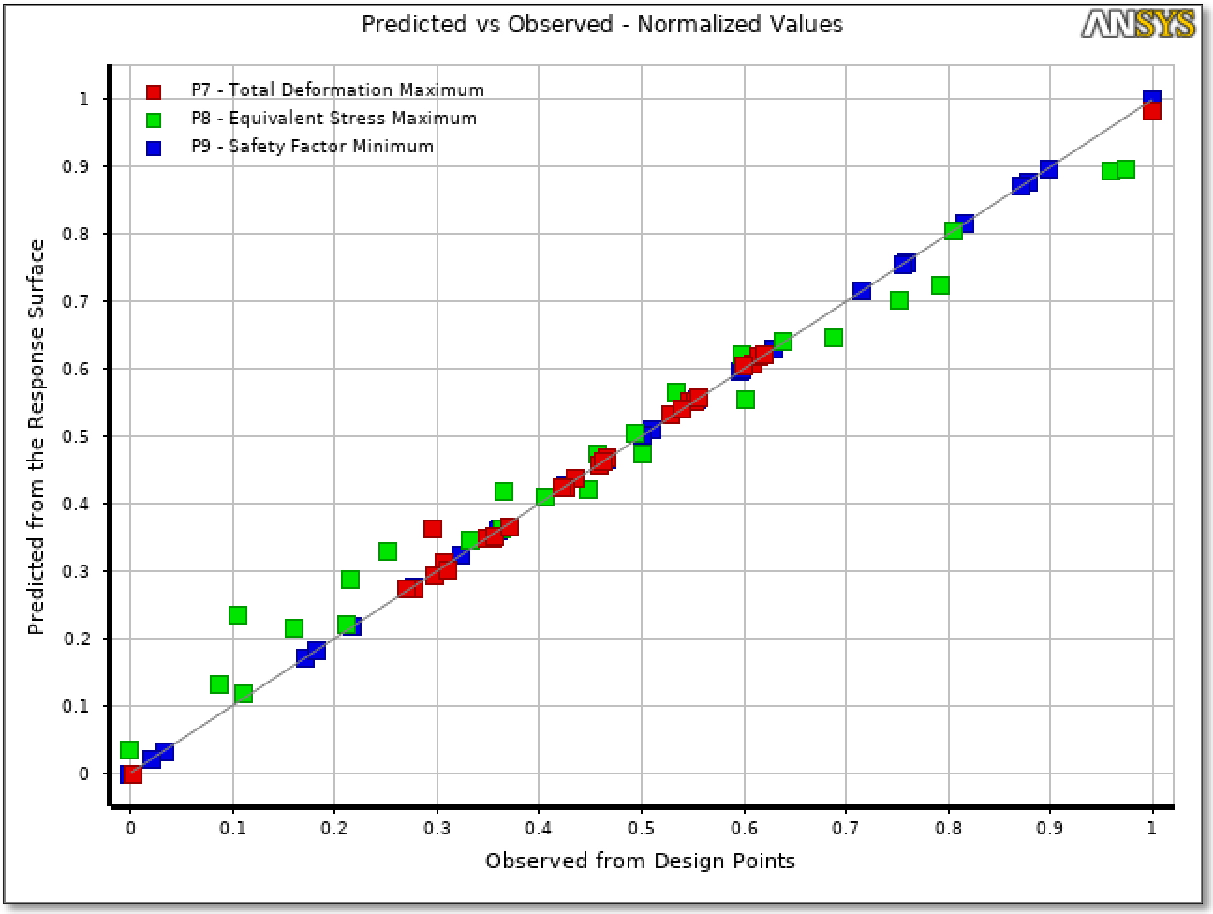


Figure 6.13: Goodness of fit

Spider charts allow you to visualize the effect that changing the input parameters has on all of the output parameters simultaneously. When you solve a response surface, a Spider chart appears in the Outline pane for the default response point. You can use the slider bars in the Properties pane for the chart to adjust values for input parameters to visualize different designs. You can also enter specific values. In the top left of the Chart pane, the parameter legend box allows you to select the parameter that is in the primary (top) position. Only the axis of the primary parameter is labeled with values.

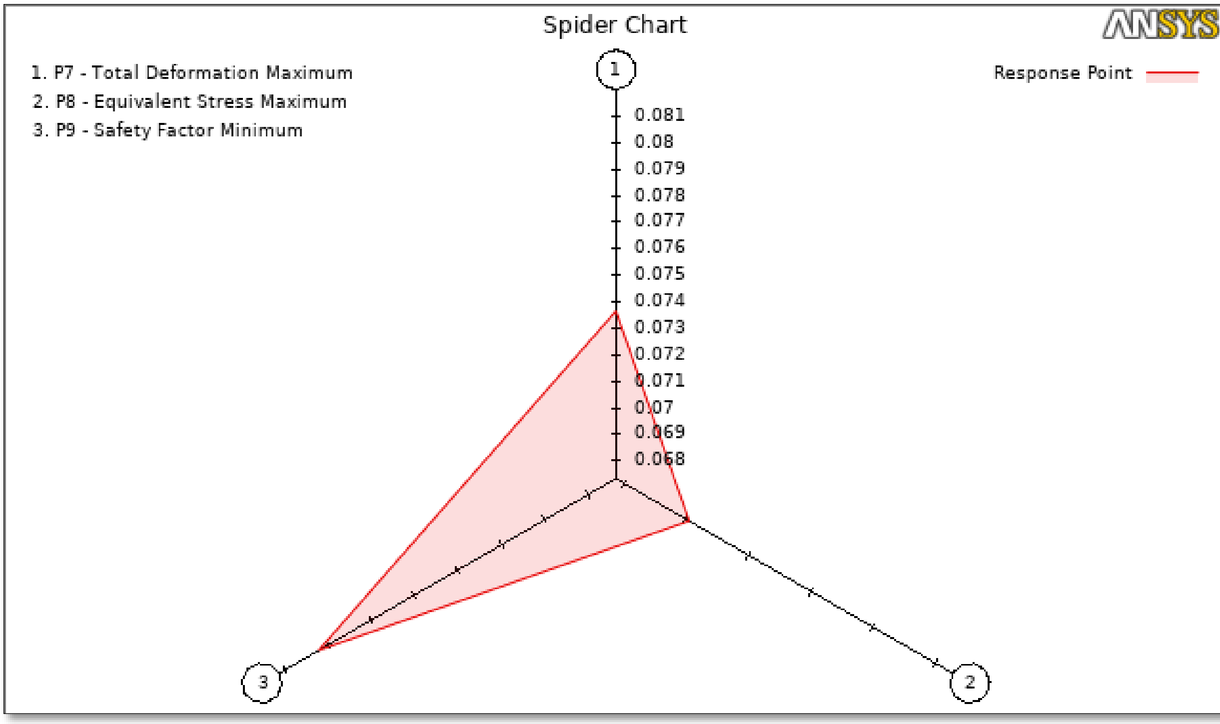


Figure 6.14: Spider chart for the output

6.2.2. Goal-Driven Optimizations

DesignXplorer offers two different types of goal-driven optimization systems: Direct Optimization and response surface optimization.

Direct Optimization system has only one cell, which utilizes real solves rather than response surface evaluations. The available optimization methods are Screening, NLPQL, MISQP, Adaptive Single-Objective, and Adaptive Multiple-Objective.

Response Surface Optimization System draws its information from its Response Surface cell and so is dependent on the quality of the response surface. The available optimization methods are Screening, Multi-Objective Genetic Algorithm (MOGA), (NLPQL), and (MISQP), which all use response surface evaluations rather than real solutions.

In this parametric optimization, *Response Surface Optimization* with MOGA is used. All the objectives and constraints are given in Figure 6.17. On the sample point chart (Figure 6.18) all the design point are provided. The results of the Response Surface optimization are also very likely to provide design candidates that cannot be manufactured. For example, the thickness spline way for candidate-3 of 9.0292 mm is likely difficult to achieve (Figure 6.19). However, because all information about the variability of the output parameters is provided by the source of design point data, whether a Response Surface cell or another Design Exploration cell, can easily find an acceptable design candidate close to the one indicated by the optimization. In this manner, the best candidate (Candidate-3) modified as in Table 6.3 is selected. The dimensional values after parametric optimization are given in Appendix B.

Table of Schematic E4: Optimization

	A	B	C	D
1	⊟ Optimization Study			
2	Minimize P7; P7 >= 0.071 mm	Goal, Minimize P7 (Default importance); Strict Constraint, P7 values greater than or equals to 0.071 mm (Default importance)		
3	Minimize P8; P8 >= 141 MPa	Goal, Minimize P8 (Default importance); Strict Constraint, P8 values greater than or equals to 141 MPa (Default importance)		
4	Maximize P9; P9 <= 1.8	Goal, Maximize P9 (Default importance); Strict Constraint, P9 values less than or equals to 1.8 (Default importance)		
5	⊟ Optimization Method			
6	MOGA	The MOGA method (Multi-Objective Genetic Algorithm) is a variant of the popular NSGA-II (Non-dominated Sorted Genetic Algorithm-II) based on controlled elitism concepts. It supports multiple objectives and constraints and aims at finding the global optimum.		
7	Configuration	Generate 5000 samples initially, 1000 samples per iteration and find 3 candidates in a maximum of 20 iterations.		
8	Status	Converged after 10724 evaluations.		
9	⊟ Candidate Points			
10		Candidate Point 1	Candidate Point 2	Candidate Point 3
11	P1 - Thickness of spline way	9.0191	9.0191	9.0292
12	P2 - Outer radius of spline	54.468	54.489	52.365
13	P4 - Back blade retainer	30.56	30.727	30.717
14	P5 - Corner fillet radius	47.593	50.683	50.838
15	P6 - Back radius of carriage	135.34	136.3	162.53
16	P7 - Total Deformation Maximum (mm)	0.071104	0.071121	0.071006
17	P8 - Equivalent Stress Maximum (MPa)	143.08	143.12	143.35
18	P9 - Safety Factor Minimum	1.7996	1.7922	1.7586

Figure 6.15: Optimization study, methods, and candidate points

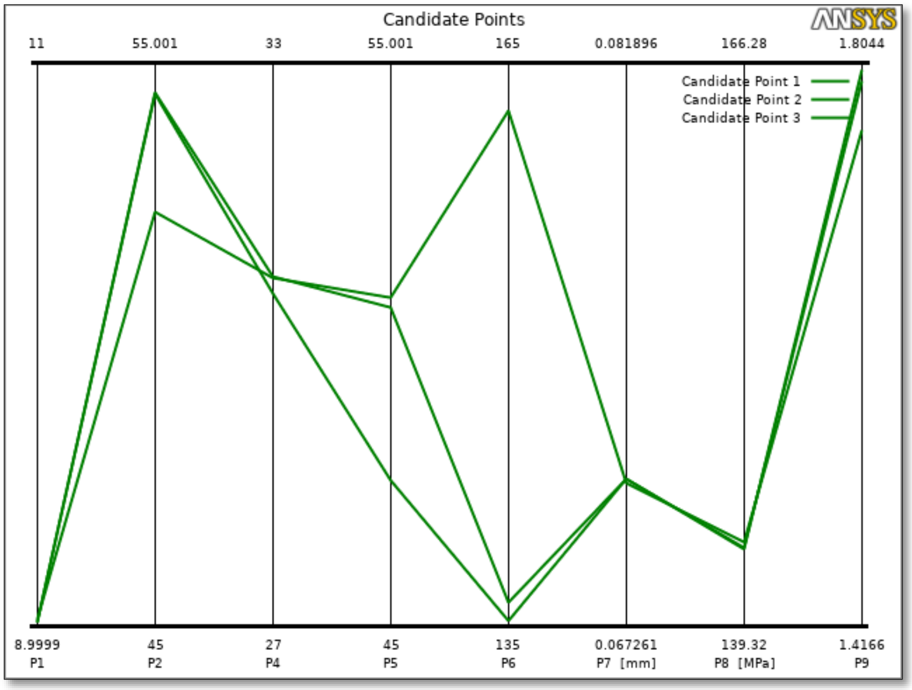


Figure 6.16: Candidate point chart

Table 6.1: The best candidates of optimization

Cand.	P1	P2	P4	P5	P6	Original	Original	Original
Cand. 1	9.02	54.47	30.56	47.54	135.34	0.071107	143.08	1.7808
Cand. 2	9.02	54.47	30.73	50.68	136.3	0.071121	143.12	1.7786
Cand. 3	9.03	52.36	30.72	50.84	162.53	0.071006	143.35	1.7692

Table 6.2: Modified parameters of the best candidate

Cand.	P1	P2	P4	P5	P6
Cand. 3 (modified)	9 mm	52.5 mm	31 mm	51 mm	162.5 mm

The ***global sensitivity chart*** shows the sensitivity of the all-output parameters with all input parameters (Figure 6.20). Global sensitivity is different from local sensitivity in that local sensitivity only considers single output parameters with all the output parameters.

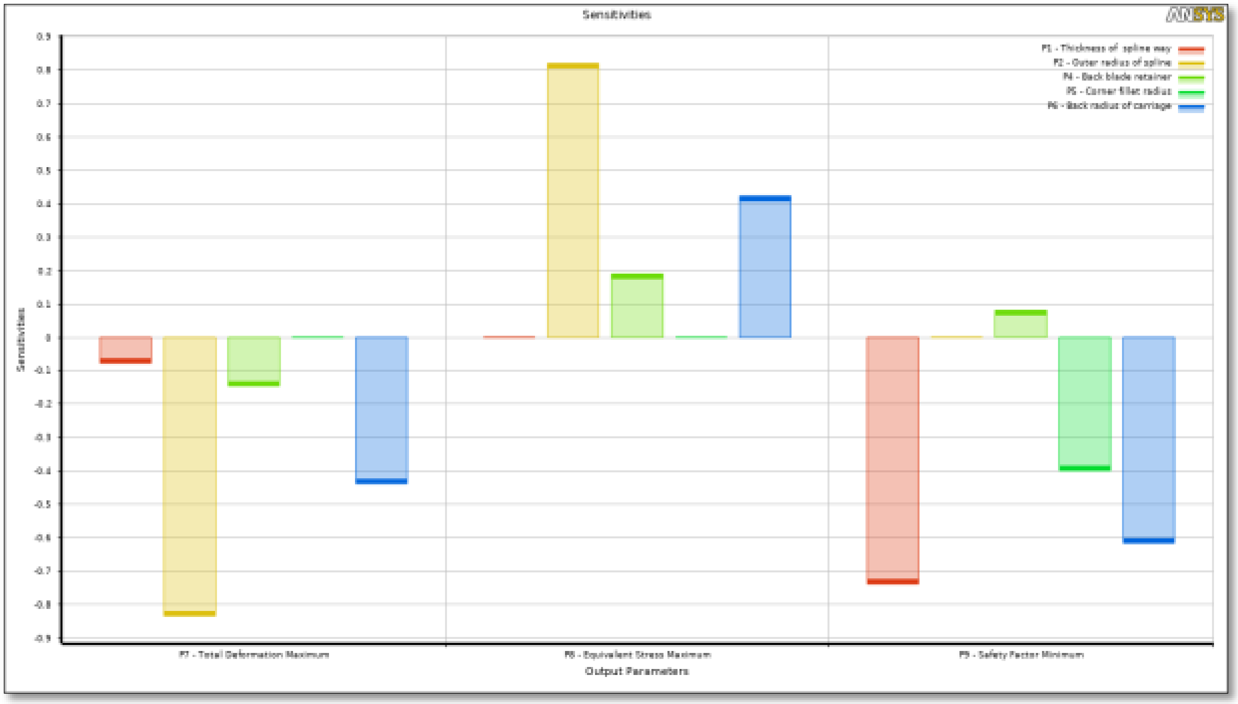


Figure 6.17: Global sensitivities of optimization to input parameters

When an optimization cell is solved, the ***Tradeoff chart*** (Figure 6.31) is created by default under results in the outline pane. The Tradeoff chart is a scatter chart representing the generated samples. The colors applied to the points represent the Pareto front to which they belong red points are the worst. Blue points are the best. Trade-off charts help to visualize possible and equivalent solutions to the optimization, providing insight for determining the best trade-offs to meet design goals. In (Figure 6.21-6.23), the two more sensitive input parameters with the output result are presented. For example, on Figure 6.21 the two higher sensitive input parameters are, P_2 (Outer radius of spline), P_6 (Back radius of carriage) are plotted with the output parameter, P_7 (Total deformation). The same technique works for Figure 6.22 and Figure 6.23.

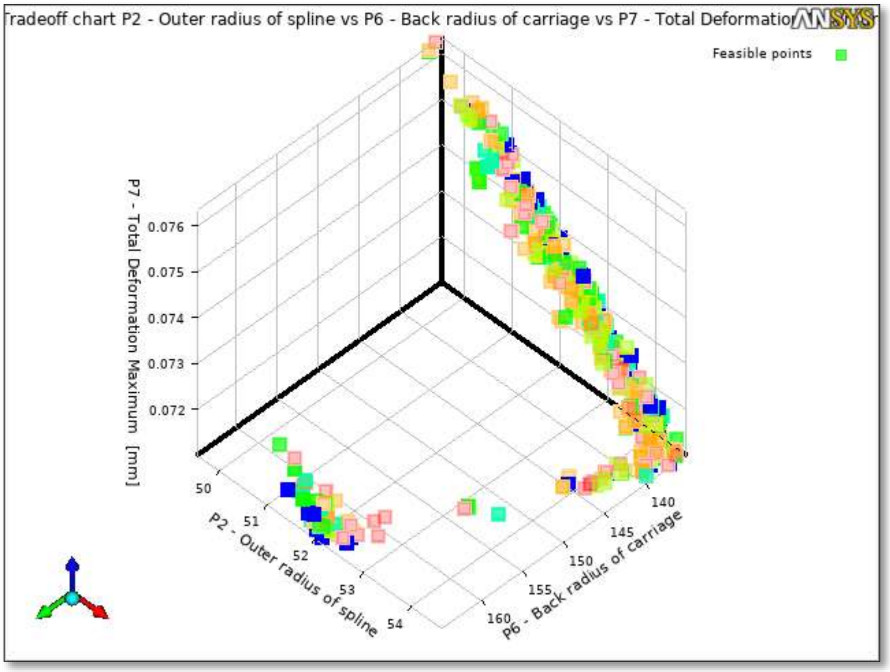


Figure 6.18: Tradeoff charts of total deformation maximum

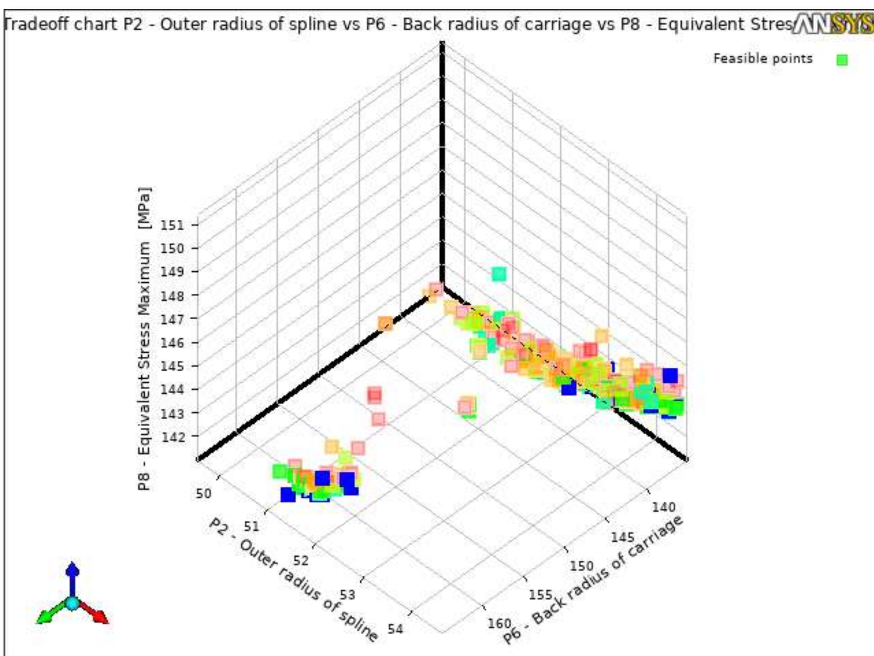


Figure 6.19: Tradeoff charts of equivalent stress maximum

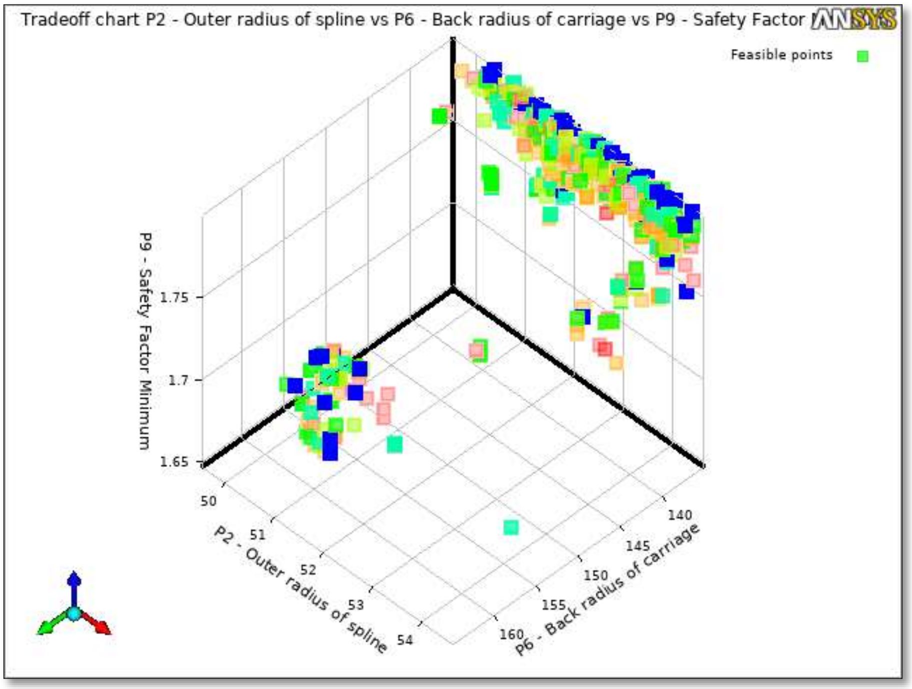


Figure 6.20: Tradeoff charts of safety factor minimum

The blade carriage weight before topology optimization, after topology optimization and after parametric optimization is 13.7 kg, 11.3 kg and 11.7 kg respectively.

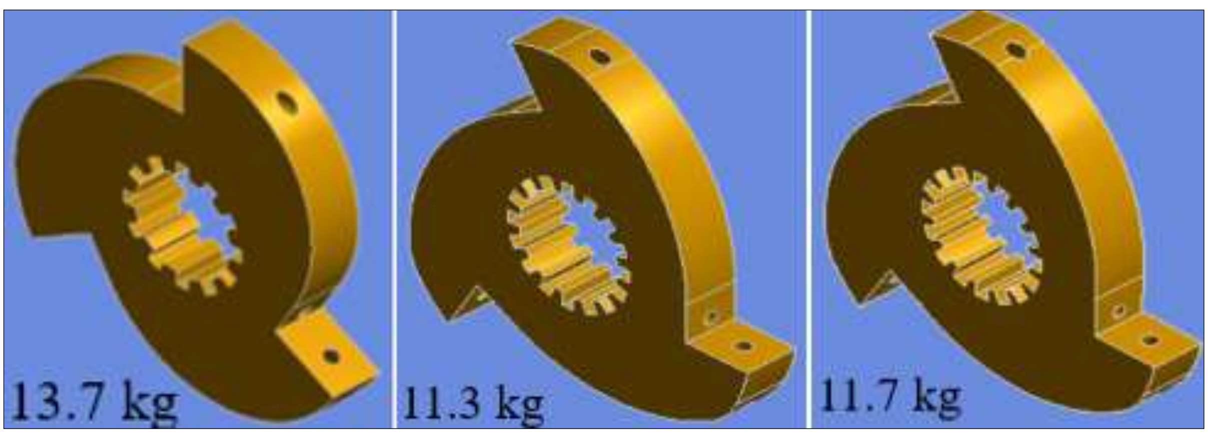


Figure 6.21: The original, topology optimized and parametric optimized models

6.3. RESULT SUMMARY

In the conceptual design of the rotor three different concepts (Flat, scissor, and staggered) are provided. In the process of concept selection, the third concept (staggered) with a little modification from original one gets a higher percentage than the rest of the concept variant. The process of concept selection takes place by examining the concepts with different design criteria and some technical feasibility.

The second topic addressed in the conceptual design is the mechanism of attaching the shaft with blade carriage. Here also three different attachment mechanism are presented, then they are checked with FEA on Ansys static structural analysis. The three-mechanism provided are:

1. Cylindrical shaft welded upon the shaft
2. Hexagonal shaft inserted into the several hexagonally slotted carriage and fastened by bolt from the other end
3. Splined shaft inserted into the several spline shaped slot carriages and fastened by bolt from the other end

As the FEA result shows the equivalent Von-Mises stress is 216.92 MPa, 45.483 MPa, and 45.479 MPa respectively. Here the result of the first mechanism is substantially above the safety factor of most shredding machine rotor which is between (2-5). Even if the second and the third has close stress concentration, the third one technically fails. This is because when the carriage is consecutively inserted in to the hexagonal shaft the gab of the jaw that created between two nearby carriage is too wide.

Eventually, the optimization of one part (blade carriage) of the rotor is considered. This is due to size and number of this part can affects the performance of the rotor. The first stage of the optimization is topology optimization, where the topology of the part is optimized. Originally, the part with rough modelling is used, with the objectives of minimizing the mass of the part. As the result the 17.7 % mass is minimized. However, for the further work it is possible to minimize the mass by removing material from some less stressed area and providing holes and other features up on the surface of the carriage. For the future work it is precisely stated that it is possible to do so.

The second stage of optimization is parametric optimization. In this stage topology optimized part (blade carriage) is used with originally parametrized dimension. Then, in the parametric optimization lower and upper bound of the parameters provided. The aim of this optimization is to find the values of the parameters that minimize deformation and stress of the component. With this upper and lower bound 27 design of experiment is automatically provided by Ansys optimization module. Then 27 of the design points are checked and from these three best candidates are extracted as the result. From these three candidates, one of the best candidates is selected with modification.

CHAPTER SEVEN

7. CONCLUSION AND RECOMMENDATION

7.1. CONCLUSION

In the conceptual design of this thesis work, three concept variants of single shaft plastic shredding machine rotor are compared with different design specifications. The three concept variants are flat arrangement, scissor arrangement, and staggered arrangement and their weighting percentages are 65.42%, 64.42%, and 66.75% respectively. From these concept variants, a staggered arrangement is selected as it is weighting has the maximum value.

The other point addressed in the conceptual design is the attachment mechanism between the shaft and blade carriage. As an alternative, three different mechanisms are provided. Namely, cylindrical, hexagonal, and splined. By conducting static structural analysis on three with the same boundary condition and loading the total deformation maximum result is 0.034 mm, 0.0031 mm, and 0.028 mm whereas the equivalent von-mises stress for cylindrical, hexagonal, and splined shaft are 216.92 MPa, 45.483 MPa, and 45.478 MPa respectively. Standing on this static structural analysis result one recommends cylindrical shaft welded on blade carriage for design simplicity and recommends splined shaft mechanically coupled with splined blade carriage for strength. However, in this work splined shaft with a splined carriage is selected and used for further analysis.

Considering the staggering arrangement and splined shaft further Topology Optimization (TO) is carried out on the blade carriage: one of the main components of the shredder rotor. The objectives of this TO is to get the appropriate geometry that can withstand the loading condition and weight minimization of the blade carriage. Accordingly, in this TO 17.5% weight is reduced: from 13.7 kg to 11.3 kg. For this optimization Ansys Workbench TO Module is utilized.

Additionally, Parametric Optimization (PO) is also carried out on the blade carriage. For PO Design Exploration module is used. Before exporting to Ansys Workbench, parametrization of blade carriage is done on SolidWork® package. From all the parameters that are parametrized on SolidWork®, only five main input parameters are checked and considered in Ansys® for the PO. The five input parameters are the thickness of the spline way, the outer radius of the spline, back blade retainer, corner fillet radius, a back radius of the carriage and the three output parameters are the total deformation maximum, equivalent stress maximum, and safety factor minimum. From Design Exploration response surface, response surface optimization, and six-sigma analysis. This parametric optimization has resulted in three best candidates and from these best candidates, one best of best candidate is used to model the final geometry of blade carriage. Afterall the final model of the shredder rotor is modeled with optimized part geometry.

Eventually, this work is the first stage in the development of shredder machine: which is planned for future work. After PO the mass of the model is little bit increased to 11.7 kg.

7.2. RECOMMENDATION FOR FUTURE WORK

Based on the study reported in this thesis, the following are recommended for future work: In this thesis, the smoothing and modification of the model after topology optimization is carried out manually on SolidWork®. Thus, using software that can do this automatically is recommended for future work.

In parametric optimization, all the parameters that determine the geometry of the blade carriage might be considered in the analysis. Here only five input parameters are considered. Rather than static analysis, if the dynamic analysis is conducted it may simulate the actual condition of the components.

- Conducting Fatigue life and modal analysis on the assembly
- Conducting FEA on each and every component
- Further topology optimization
- Including all the parameters of blade carriage in parametric optimization
- Using another optimization package than Ansys®
- Conducting material optimization

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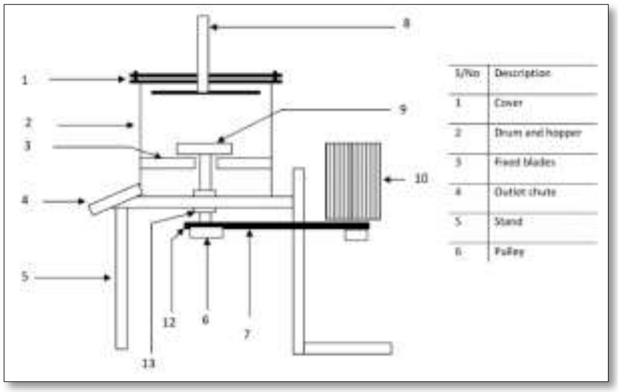
APPENDIX A: ALTERNATIVE MACHINES OBSERVED FROM LITERATURE



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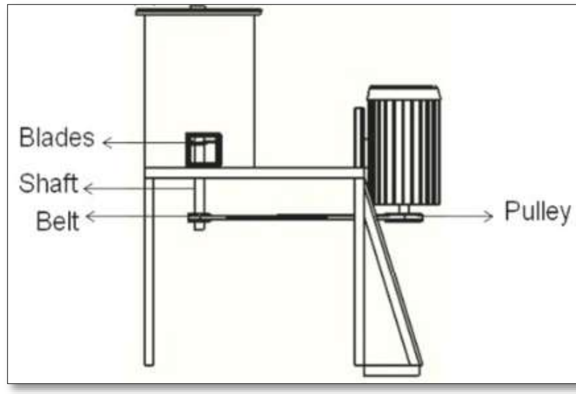

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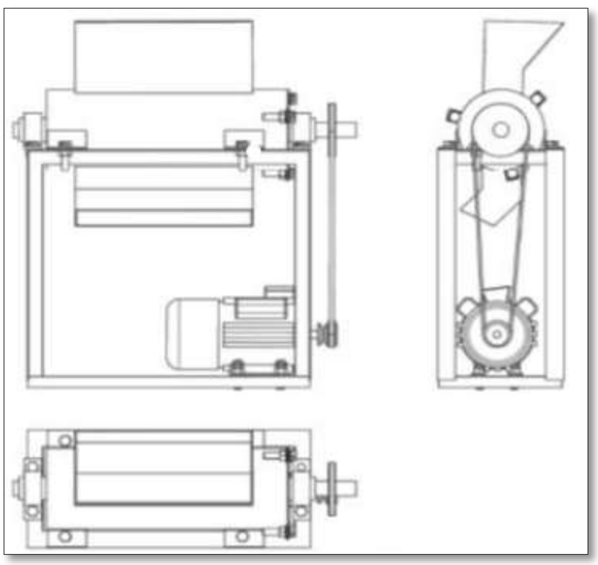

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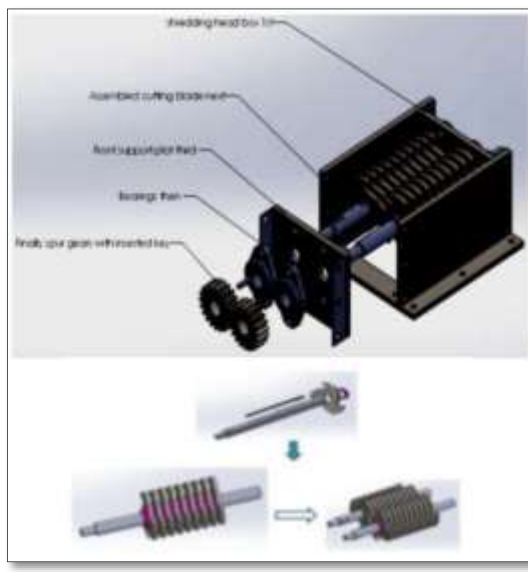
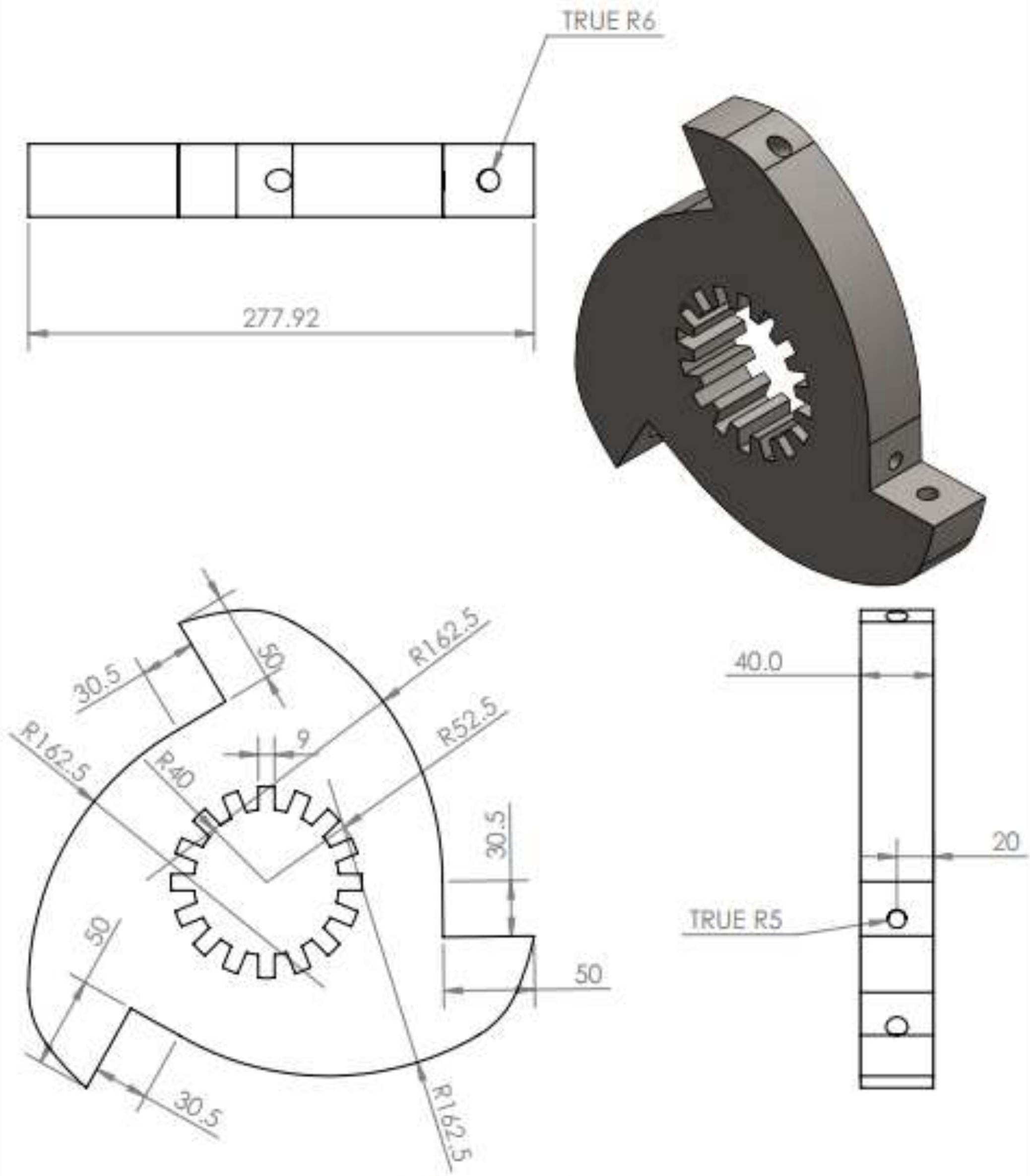


(d) Developed by [30]

APPENDIX B: PARTS OF THE SHREDDER ROTOR



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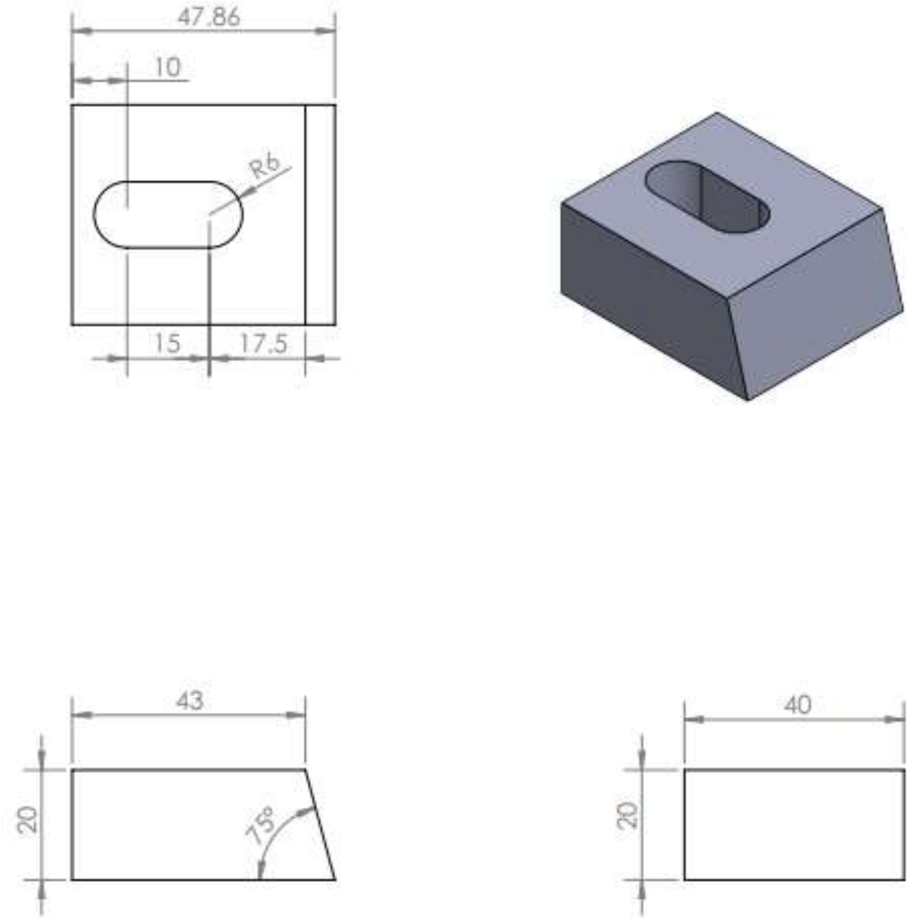

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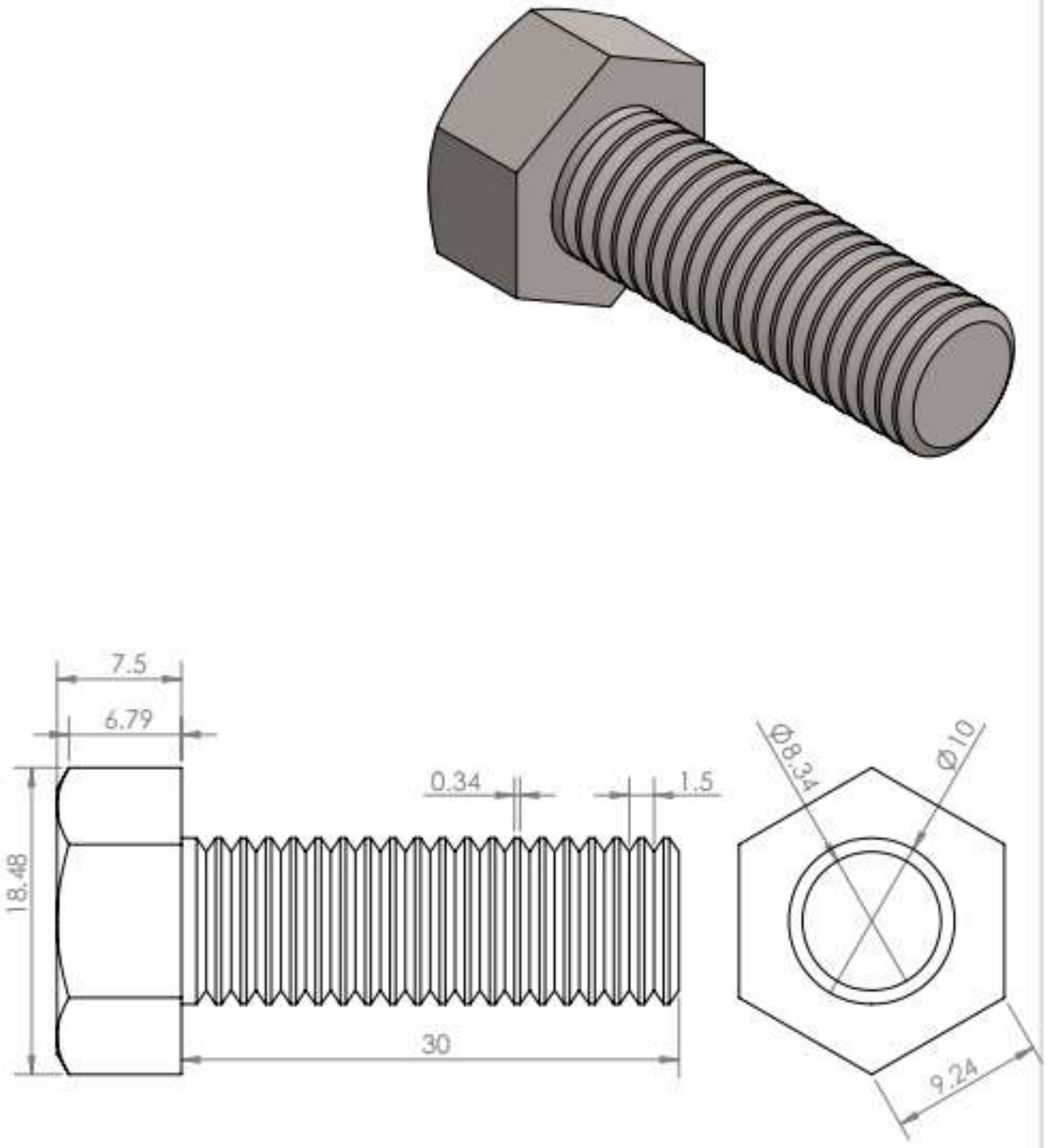

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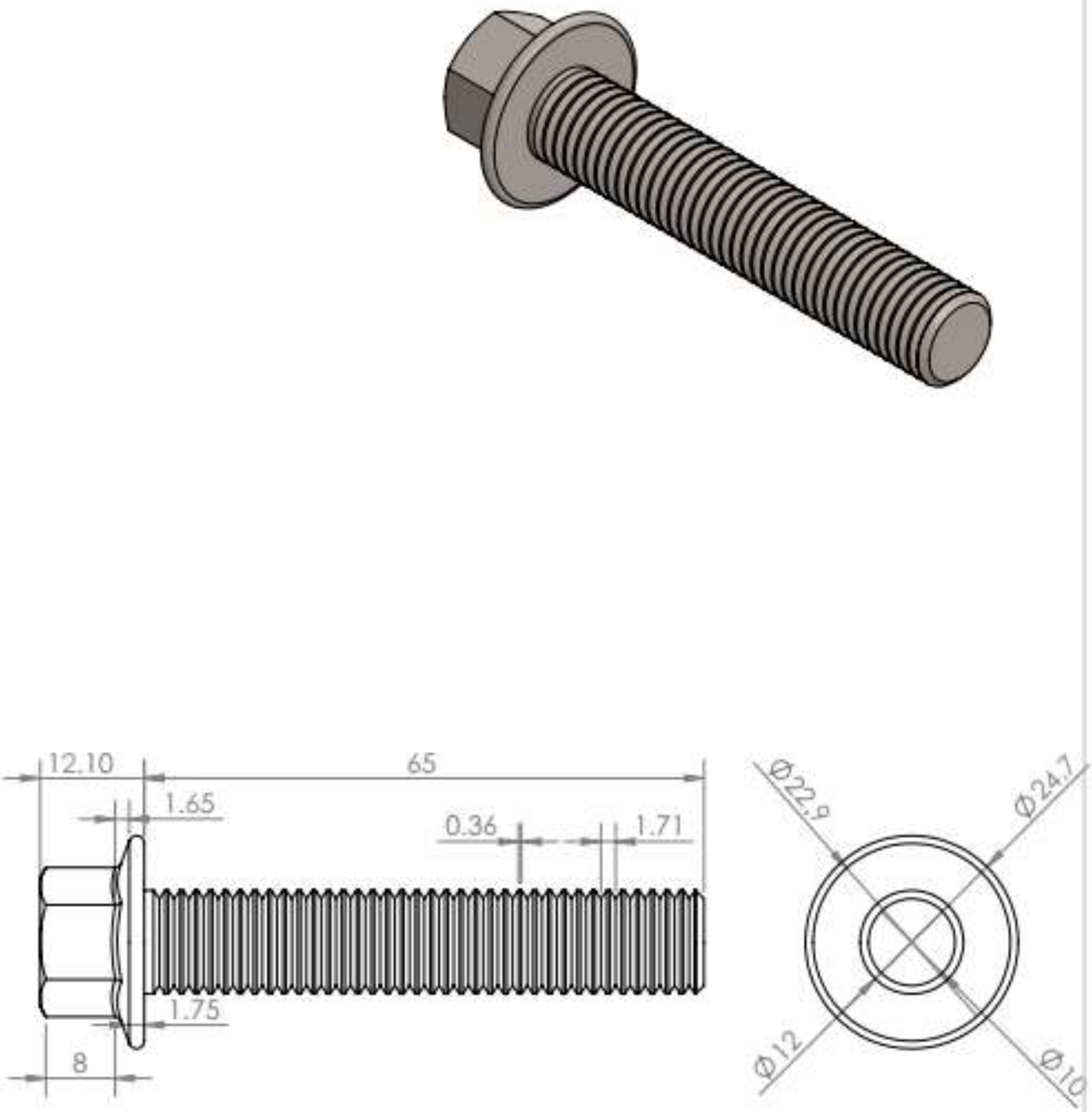

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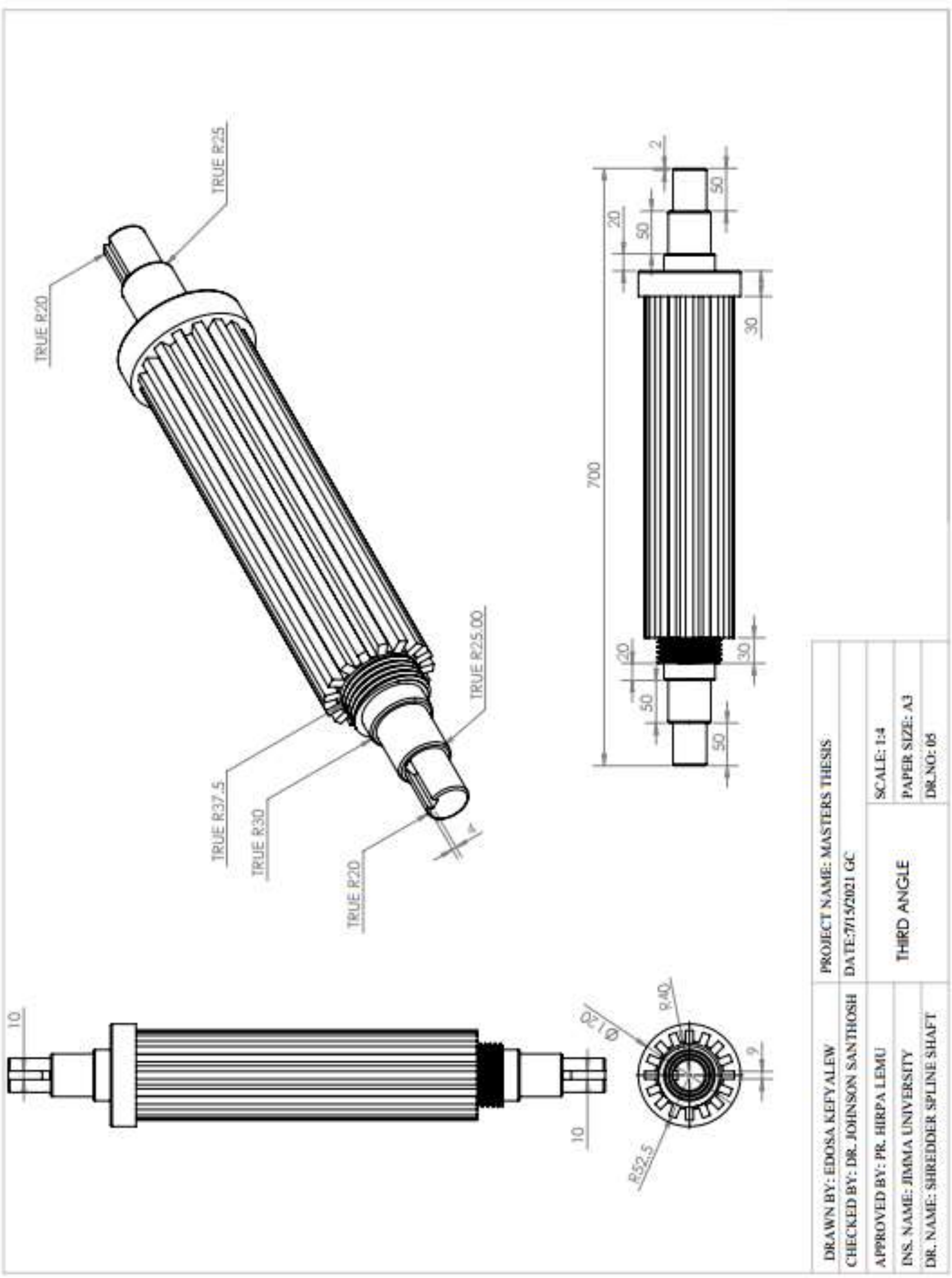
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R52.5
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CHECKED BY: DR. JOHNSON SANTHOSH
APPROVED BY: PR. HIRPA LEMU
INS. NAME: JIMMA UNIVERSITY
DR. NAME: SHREDDER SPLINE SHAFT
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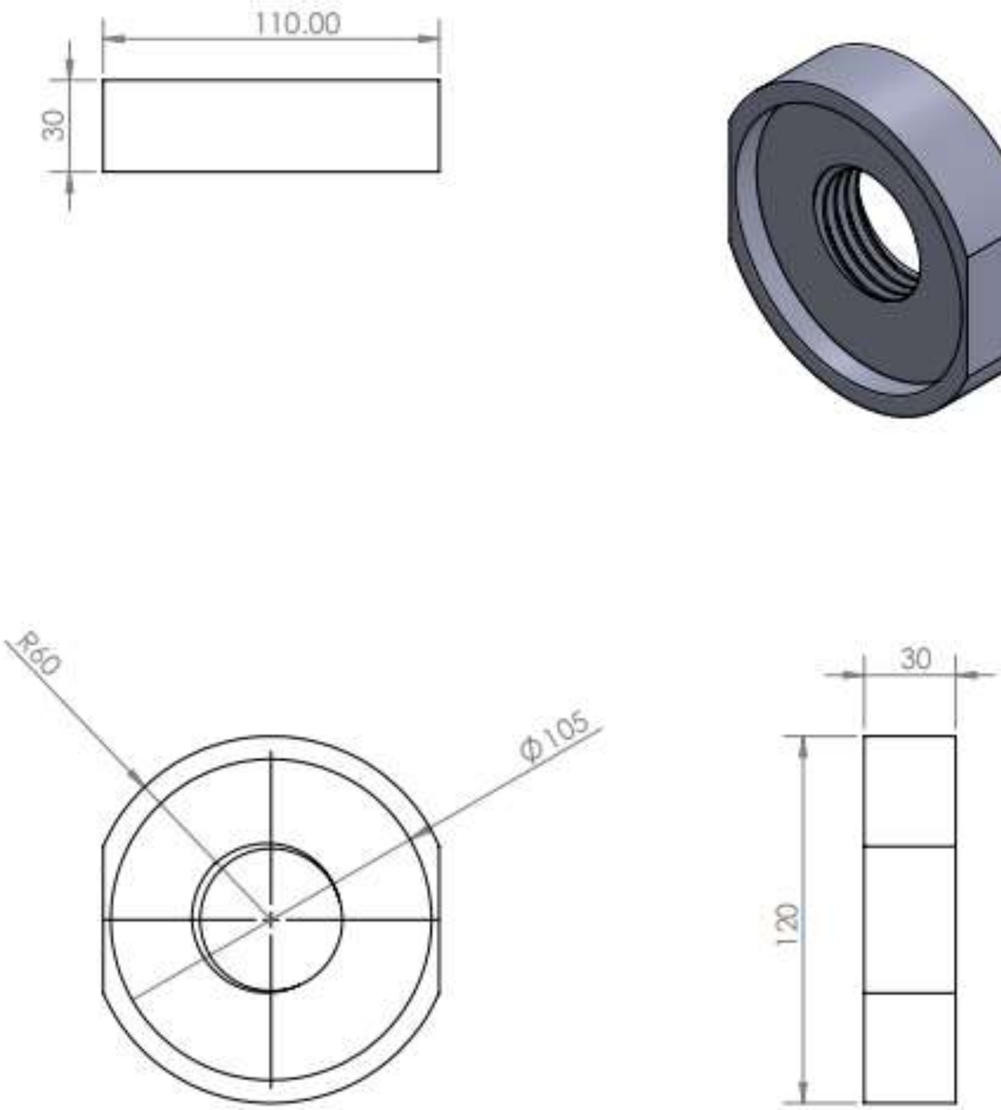

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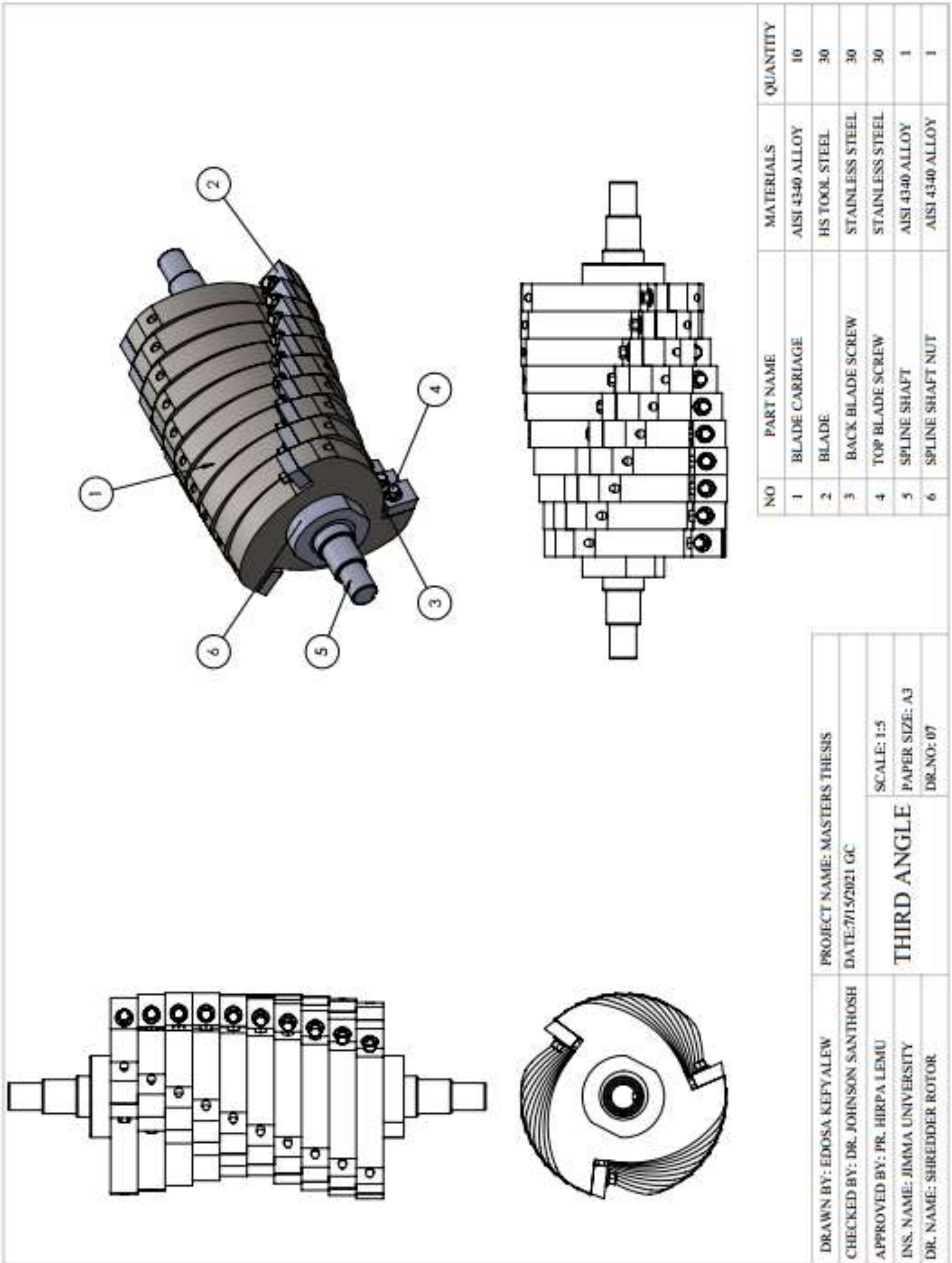
1
2
3
4
5
6
NO
PART NAME
MATERIALS
QUANTITY
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2 BLADE HS TOOL STEEL 30
3 BACK BLADE SCREW STAINLESS STEEL 30
4 TOP BLADE SCREW STAINLESS STEEL 30
5 SPLINE SHAFT AISI 4340 ALLOY 1
6 SPLINE SHAFT NUT AISI 4340 ALLOY 1
DRAWN BY: EDOSA KEFYALEW
PROJECT NAME: MASTERS THESIS
CHECKED BY: DR. JOHNSON SANTHOSH
DATE:7/15/2021 GC
APPROVED BY: PR. HIRPA LEMU
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DR. NAME: SHREDDER ROTOR
DR.NO: 07

APPENDIX C: OUTLINES OF SCHEMATIC

Outline of Schematic E4: Optimization

	A	B	C
1		Enabled	Monitoring
2	Optimization		
3	Objectives and Constraints		
4	Minimize P8; P8 >= 141 MPa		
5	Maximize P9; P9 <= 1.8		
6	Minimize P7; P7 >= 0.071 mm		
7	Domain		
8	Static Structural (A1)		
9	P1 - Thickness of spline way	☑	
10	P2 - Outer radius of spline	☑	
11	P4 - Back blade retainer	☑	
12	P5 - Corner fillet radius	☑	
13	P6 - Back radius of carriage	☑	
14	Parameter Relationships		
15	Convergence Criteria		
16	Results		
17	Candidate Points		
18	Tradeoff		
19	Samples		
20	Sensitivities		

Outline of Schematic F2: Design of Experiments (SSA)

	A	B
1		Enabled
2	Design of Experiments (SSA)	
3	Input Parameters	
4	Static Structural (A1)	
5	P1 - Thickness of spline way	☑
6	P2 - Outer radius of spline	☑
7	P4 - Back blade retainer	☑
8	P5 - Corner fillet radius	☑
9	P6 - Back radius of carriage	☑
10	Output Parameters	
11	Static Structural (A1)	
12	P7 - Total Deformation Maximum	
13	P8 - Equivalent Stress Maximum	
14	P9 - Safety Factor Minimum	
15	Charts	
16	Parameters Parallel	
17	Design Points vs Parameter	

Outline of Schematic D3: Response Surface

	A	B
1		Enabled
2	Response Surface	
3	Input Parameters	
4	Static Structural (A1)	
5	P1 - Thickness of spline way	☑
6	P2 - Outer radius of spline	☑
7	P4 - Back blade retainer	☑
8	P5 - Corner fillet radius	☑
9	P6 - Back radius of carriage	☑
10	Output Parameters	
11	Static Structural (A1)	
12	P7 - Total Deformation Maximum	
13	P8 - Equivalent Stress Maximum	
14	P9 - Safety Factor Minimum	
15	Min-Max Search	☑
16	Refinement	
17	Tolerances	
18	Refinement Points	
19	Quality	
20	Goodness Of Fit	
21	Verification Points	
22	Response Points	
23	Response Point	
24	Response	
25	Local Sensitivity	
26	Local Sensitivity Curves	
27	Spider	
*	New Response Point	