DESIGN, DEVELOPMENT AND PERFORMANCE EVALUATION OF A DIESEL ENGINE DRIVEN MECHANICAL SUGARCANE HARVESTER

BY:

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DEPARTMENT OF MECHANICAL SYSTEM AND VEHICLE ENGINEERING

SCHOOL OF MECHANICAL, CHEMICAL AND MATERIAL ENGINEERING

A Thesis Submitted in Partial Fulfillment of the Requirements for the Award of the Degree of Master of Science in Agricultural Machinery Engineering

Office of the Graduate Study

Adama Science and Technology University

Adama, Ethiopia

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ADVISORS APPROVAL SHEETS

To: Mechanical System and Vehicle engineering

Subject: Thesis submission

This is to certify that the thesis entitled "**Design, development and performance evaluation of diesel engine operated mechanical sugarcane harvesting machine**" submitted in partial fulfillment of the requirement's for the degree of the Masters in Agricultural machinery engineering, the Graduate program of the department of Mechanical System and Vehicle engineering, and has been carried out by Yemane Woldeyesus Ambo Id. No. 18087/11, under my supervision.

Therefore, I recommend that the student has fulfilled the requirements and hence here he can submit the thesis to the department.

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DECLARATION

I hereby declare that this MSc Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

Name: Yemane Woldeyesus Ambo

Signature: ____________________

This MSc Thesis has been submitted for examination with my approval as a thesis advisor.

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Date of submission: ___________

APPROVAL OF BOARD OF EXAMINERS

We, the undersigned, members of the Board of Examiners of the final open defense by **Mr. Yemane Woldeyesus Ambo [PGR/18087/11]** have read and evaluated his thesis entitled "**Design, development and performance evaluation of the diesel engine driven mechanical sugarcane harvesting machine**" and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of Master of Science in Agriculture Machinery Engineering complies with the regulation of the university and meets the accepted standards with respect to originality and quality.

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LIST OF ACRONYMS

AGMA	American Gear Manufacturing Association
ASABE	American Society of Agricultural and Biological Engineering
ASME	American Society of Mechanical engineers
BMI	Body Mass Index
CSA	Central Statistical Agency
EER	Energy Expenditure Rate
ETB	Ethiopian Birr
EU	European Union
hP	Horse Power
HR	Heart rate
Kb	Combined shock and fatigue factors applied to bend moment
KM	Kilometer
Kt	Combined shock and fatigue factor applied to torsional moment
LCC	Life Cycle Cost
Mb	Bending moment
Mt	Torsional moment
MT	Metric Tones
Ms	Mild Steel
OCR	Oxygen Consumption Rate
PPE	Personal Protective Equipment
PR	Pulse Rate
rpm	Revolution per minute
SNNPR	South Nations Nationalities and Peoples Representatives

ABSTRACT

Sugar production in Ethiopia started in 1954/55 when the Wonji Sugar Factory was commissioned and produced 15,843 tons of white sugar in the first campaign. Sugarcane harvesting is the most costly operation in sugarcane farming. Although more sophisticated self-propelled sugarcane harvester has been using in developed countries while manual harvesting was still practiced in most undeveloped countries like Ethiopia. In areas where manually sugarcane harvesting, a simple, efficient and less complicated mechanical harvesting machine aid was desirable. Manual sugarcane harvesting requires intensive labors, quite a lot of money, and time-consuming tasks which involves considerable human drudgery. So this study focused on the design, develop and performance evaluation of sugarcane harvesting machines that is cheap, easily affordable by the farmers and sugar factories easy to maintain and less laborious to use. The developed sugarcane harvesting machine consists of a frame, discs with a cutting unit, shaft, safety frame, wheels, and five horsepower diesel engines. Hence this project work overcomes these problems and aims to develop a small-scale sugarcane harvesting machine. The materials used for construction and manufacturing was by considering the different parameters during operation and harvesting. The developed sugarcane harvester was tested in the laboratory and in the field. In a laboratory test, the machine was checked for its specifications and operations. In the field physical structure of the sugarcane, speed of the operators, pulse rate, and the performance evaluation of the machine was made in terms area covered, and other related parameters. The performance evaluation was carried out at three levels of cutter speeds (1000 rpm, 1085 rpm and 1170 rpm). The mean area coverage, field capacity, field efficiency and height of cut above the ground by the sugarcane harvester machine with 1085 rpm were observed to be 1.9 $\times 10^{-3}$*ha, 3.8 x*10^{-3}*ha/hrs, 86.10% and 5.8 cm respectively. The harvesting cost to finish 118.5* m^2 *areas was 148.71 ETB. The cost of fabrication for the development of the sugarcane harvester was 21,498.65 Birr. Based on the performance evaluation results, it is concluded that the prototype harvester was easy, efficient and affordable by sugarcane producing farmers and sugar factory of Ethiopia.*

Key words: Field capacity, Sugarcane harvester machine, Sugarcane harvesting cost, height of cut, Sugarcane

CHAPTER ONE

1. INTRODUCTION

1.1. Background and justification

Sugarcane is a member of the family Gramineae, tribe Andropogoneae, and is classified in the genus Saccharum. Saccharum originated in the warm temperate to tropical regions of south Asia and Melanesia, and used for sugar production. The cultivated varieties of sugarcane, worldwide, are inter-species hybrids between the species of the Genus, Saccharum (Ibrahim, 2016).

Sugar production in Ethiopia started in 1954/55 when the Wonji Sugar Factory was commissioned and produced 15,843 tons of white sugar in the first campaign. The development of the sugarcane plantation was started on 5000 hectares in the upper reaches of the Awash basin, 100 km, South East of Addis Ababa. In some areas, sugarcane is used to prepare local beverages called "Karibo", while in others the leaves are used for thatching and as firewood (Esayas Tena *et al*., 2016).

Ethiopia produces 340, 000 tons of sugar on 25, 000 ha of land annually, and about 20,000 tons a year were sold to the EU. However, Ethiopia's domestic sugar consumption was considerably higher (1.26 times) than its production. Therefore, the country imports about 152, 000 MT of sugar per year to satisfy domestic demand (Mamoun, 2012). Thus, there is a high need to increase the production and productivity of sugarcane to have a reliable supply of sugar in the country. According to the report by CSA (2018), sugarcane is produced in about 29,536.49 ha with 1,090,575.00 holdings in different parts of the country. But all the production was not usually used for industrial purposes. It was noticeably used for household consumption (chewing), selling for immediate cash, and feeding livestock. Sugarcane harvest is a complex logistical operation that involves the cutting and loading of cane in the fields, the harvesting operation must be carefully planned and coordinated to avoid any waste of valuable resources. Harvesting of Sugarcane at the proper time i.e., peak maturity, by adopting the right technique is necessary to realize the maximum weight of the mill (Yousra, 2012).

Cane harvesting is the most costly operation in sugar cane farming. Variable sizes and designs of semi mechanization sugarcane harvesting machinery are available. Full mechanization systems may be whole stalk harvesting systems or chopper harvesting systems. The important issues that have to be addressed are improving harvesting rates and reducing extraneous matter levels of the cane delivered to the factory. In Ethiopia sugar cane harvesting system is manual. It requires several laborers to perform the work. During this operation, there is a chance of damage by insects, snake, injuries, muscle, and some other parts of pain (Abdel and Hemeida, 2015).

Different types of harvesting machines are available in the market namely paddy harvester, tea harvester, potato harvester, wheat harvester, and sugarcane harvester as mentioned above all are available on small scale except the sugarcane harvesting machine (Adarsh *et al*., 2013). Mechanization of sugarcane harvesting is an essential input to modern agriculture, as it enhances better productivity, besides reducing human drudgery and the cost of cultivation. The cost of sugarcane harvesting by the mechanized process is almost one-third of the complete manual process (Abdel and Hemeida, 2015).

The main aim of this study was to design, fabricate and evaluate the performance of diesel engine motor-driven sugarcane harvesting machines which were made from locally available materials, cheap, but strong enough to perform those tasks. The sugar harvesting machine was developed and undertaken in the area where one of the Federal sugarcane factory; Wonji Shoa sugar factory Dodota sub-branch work shop. The developed six horsepower diesel engine driven cane harvester components were rotating disc with a cutting blade at the bottom and top which was connected by bolt and nut, handle, safety frame, supporting frame, wheels.

1.2. Statement of the problem

Sugarcane harvesting needs a special machine and which can perform a different operation at a time. In Ethiopia, there were more than 8 sugarcane factories. But sugar consumption in the country was greater than its production (Mamoun, 2012). Sugarcane mechanization in most cane plantations of sugar states is rare. Nowadays, self-propelled sugarcane harvester machine was not introduced. Moreover, harvesting of the sugarcane from the field of smallholder farmers and sugar state had been performed by intensive human labor in hard and harsh weather conditions.

In the sugar states, many seasonal laborers were required for harvesting. The shortage of seasonal laborers and improper harvesting of cane was the major problems of cane production.

Improper harvesting leads to loss of sugarcane, poor juice quality, and problems in milling due to extraneous matter and low quality of sugar yield. They cut sugarcane above the ground level with distance to avoid the strike of the knife with soil but the maximum sugar content was at the bottom of the cane. Labors need frequently for taking rest, and they experience sustained injuries from excessive stress on the joints and muscles of the body. The cutting tool and motion involved directly stresses the laborers. A cutting tool that has not been designed which can lead to unnecessary strains in the body's muscle system, resulting in injuries.

To solve the aforementioned problems, designing and introducing a mini semi-mechanical sugarcane harvesting machine that can improve quality sugarcane, reduces intensive seasonal labor, make operation simple, uncomplicated, safe, and environmentally friendly one is essential.

1.3. Objectives of the study

1.3.1. General objective

The general objective of this study were to design, develop and performance test of a diesel engine driven mechanical sugarcane harvester

1.3.2. Specific objectives

- To design a sugarcane harvesting machine components and parts
- To develop and manufacture the sugarcane harvesting machine
- To test the performance of the sugarcane harvesting machine

1.4. Significance of the study

Sugarcane harvesting needs high energy and can be operated with care due to the high chance of injuries. The sugar factory in Ethiopia use manual harvesting system. Thus manual harvesting system was time consuming, less quality, not comfortable for laborers and high chance of the damage and injuries. In this study, effort was made to solve problems observed in manual harvesting system and loss due to it through design and fabrication of technically and economically compatible diesel engine driven mechanical sugarcane harvesting machine.

1.5. Scope of the study

Based on the objectives, the study conducted the performance test in the field. It includes all the processes needs to design and construct the parts of the machine such as cutter, frame, wheel or cage, and shaft. That means including decisions on the size and type of the harvester and its parts. This invention reduced the shortcomings of the manual harvesting of sugarcane and reduces importing the huge harvesting machine for small field operations.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Sugarcane morphology

Sugarcane is a large tropical plant that can produce multiple stems each of which consists of a series of nodes separated by internodes. Following germination, the terminal vegetative bud of each shoot lays down a series of nodes, each with a dormant bud and one or more rows of roots primordial and growth ring (Anon, 2004).

The stem of sugarcane is a major sink of sucrose within the sugarcane plant, rather than fruit or seed structure. Traverse cross-section through internodes reveals vascular bundles surrounded by parenchyma cells with the outer epidermis covered in an external layer of wax. Like most grasses, the sugarcane root system was fibrous and shallow. However, the plant develops buttress roots that serve to anchor the plant and some deeply penetrating roots that grow downwards for 5-7 meters allowing for water absorption under water stress (Sizuo and Rubismar, 2012).

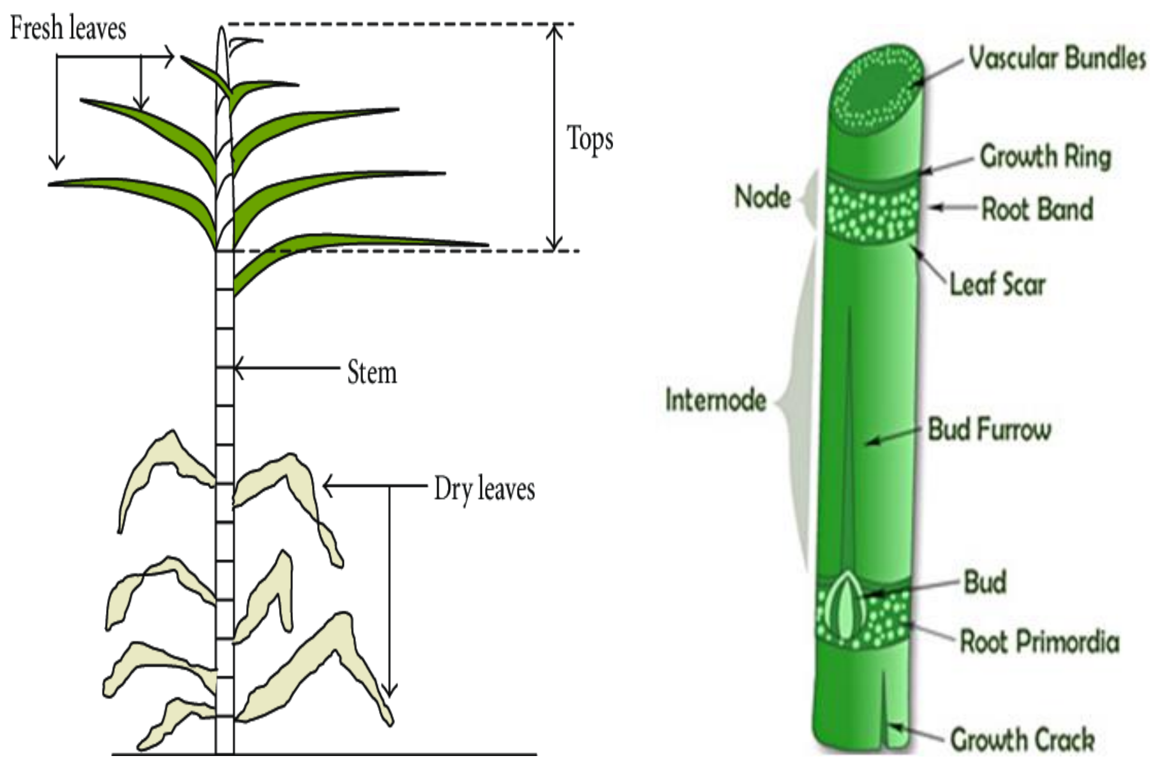

Figure 2. 1. Morphology of sugarcane

2.2. Sugarcane lodging

Major factors affecting cane lodging status are soil type, moisture level, crop variety, crop size, planting depth, hill-up, and wind. Poor drainage of irrigation water results in uneven crop growth, suckering, lodging, and increased impurities in cane. Excessive nitrogen applications can cause lodging. Some diseases and insects like sugarcane grub and pachymetra root rot may cause lodging and tipping of stalks and stools that tear out easily at harvest. Lodged or sprawled crops are harder to harvest, more difficult to gather into the harvester, and have more extraneous material than erect crops (Ibrahim and Hijaz, 2016).

The different researchers proposed the criteria to classify stalks lodging status, by which stalks were classified into 3 categories (Hankel *et al.*, 1979).

I. Erect stalks are those which present a degree of alignment with the ground of 60° or higher.
II. Lodged are those which are found between 30° and 60°.
III. Recumbent are those which are found less than or equal to 30° of inclination.

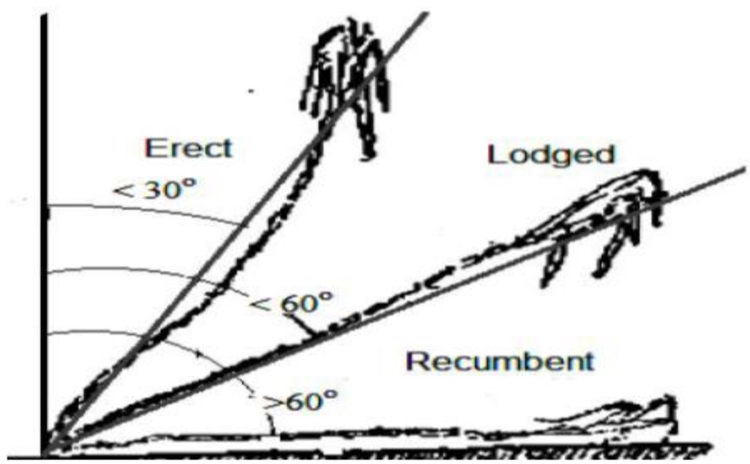

Figure 2. 2. Sugarcane lodging type

2.3. Sugarcane harvesting method

Sugarcane is harvested by hand or mechanical method. Various harvesting practices were used in sugarcane production, each requiring different harvesting technologies to ensure effective and efficient field operations. Based on how the sugarcane was presented to the harvester, harvesting practices were classified into two groups; harvesting of canes with burnt cane harvesting and harvesting of canes without burning or green cane harvesting (Ma *et.al*, 2014).

2.3.1. Burnt cane harvesting method

Hand harvesting accounts for more than half of production and was dominant in developing countries. In hand harvesting, the field was first set on fire. The fire removes dry leaves and kills insects, snakes, and rodents without harming the crop. Burning also helps in concentrating sucrose in stalks but can leads to accelerated rates of deterioration of sucrose content if not processed in a short period. Harvesters then cut the cane just above ground-level using cane knives or machetes. Hand cutters achieved daily outputs for cutting and loading of 9–12 tons in burnt cane and around 6 tons in green cane. The advent of mechanical loaders resulted in a significant improvement in output to about 12–18 tons per day in burnt cane (Ibrahim and Hijaz, 2016).

Pre-harvest burning of sugarcane was one of the most sensitive environmental issues faced by cane growers. Residents sometimes complain of inconvenience and discomfort caused by smoke and soot from cane fires. Producers have been using sugarcane burning as a standard pre-harvest practice throughout the world since the industrial revolution because it leads to reduced pest stress and reduced load for top and trash handling (Adilica, 2015).

However, burnt cane harvesting has various negative impacts. Burnt cane harvesting poses a risk of sugary deterioration, which reduces the rate of sugar extraction. Cane burning causes juice leakage, cane splits, leaves, and other leafy materials that were detached when severed stalks passed through a defoliation device (Phimpiwat *et al.*, 2016).

2.3.2. Green cane harvesting method

Green cane harvesting with trash retention was an effective way of arresting the loss of soil organic matter that characteristically occurs under conventional sugarcane production. Canes were harvested without any preconditioning such as burning or removing leafy materials before harvest. A particular mechanical device was then used to separate leafy materials and discharge them into the field. From the perspective of soil nutrient balance and environmental effects, this process may provide a more sustainable option for sugarcane harvesting compared to burnt cane harvesting. The residues left in the field could help to control weeds, reduce soil moisture loss, and decrease soil erosion (Ma *et.al*, 2014).

The effects of green harvesting followed by partial incorporation of residues and pre-harvest burning in semi-arid South Texas were conducted and checked. The Soil organic matter content after three years was increased by green harvesting compared to burning before harvest. While the effects due to green harvesting on soil properties and crop growth were relatively minor, the residue remaining on the soil presents considerable challenges in cultivation, weed control, and irrigation (Bob, 2009).

2.4. Sugarcane harvesting machine type

The development of sugarcane harvesters dates back to the late 19th century. The manually pushed harvester machine was constructed in a different country of the world. But their environment and the topography of the land were affecting their efficiency. The most sophisticated harvesting machine was used in the most developed country. For this machine, different researchers reviewed their influence of base cutter kinematic and geometric parameters, such as blade cutting velocity, disc tilt angle, blade number, blade oblique angle, and blade shape on harvesting efficiency and cutting quality (Baxter, 1975).

2.4.1. Whole stalk harvesters

In this method, the cane was only cut at the bottom of the plant rather than cutting at several points on the stalk. This machine would cut without a cleaning mechanism so it does not cut extraneous matter. In this harvesting mode, farmers usually set fire to the windrows and burned off the leafy materials. Some measurements such as harvesting performance of the machine, harvesting rate, and field efficiency were taken in South Africa for both whole stalk and green sugarcane harvester machine**s** (Meyer, 1999).

Whole-stalk sugarcane harvester machine for full mechanization of sugarcane harvesting should perform the following functions in sequence; positioning and handle the cane in respect to functional mechanisms, cut the base of cane stalk, cut the green top of the cane stalk, clean cane stalks from dry leaves, place cane stalk suitably for further operations, convey cane harvested from several furrows and place them together to form a windrow. But harvesting bent canes with these machine results in some challenge which needs bending and moving various directions. Therefore, it is difficult to arrange windrowed stalks into compact bundles needed for easy handling and transportation. Another disadvantage is that the whole stalk harvesters have limitations in dealing with high tonnage sugarcane (Baztarrica *et al.*, 2011).

In Pakistan variable-width whole stalk harvester were fabricated and evaluated. The major components of indigenously developed sugarcane harvester include hydraulically operated bottom cutter, top cutter, blower, and conveyor and all of them are fixed on a movable iron frame. For optimization, the sugarcane harvester was operated at three different gears (G_1, G_2, and G_3) and engine speed (N_1= 1800, N_2= 1900 and N_3= 2000 rpm) of the tractor and working widths (Kw_1= 0.85, Kw_2= 0.92 and Kw_3= 1.02 m) of harvester variety CP-77400 to determine the maximum field efficiency and material capacity. The results showed that maximum field efficiency was found to be 75.10 % and material capacity was 12.87 ton/hr. at G_3, N_3, and Kw_3 (Usama *et al.*, 2019).

2.4.2. Chopper harvester machine

The chopper sugarcane harvester machines perform the basal cutting, promoting the cleaning of sugarcane through gravity by the action of fans or blowers and chop the stalks 15 to 40 cm billets, unloading them onto the transport unit for transshipment. Inside the machine, the sugarcane passes through various stages from the movement of basal cutting to the loading into the vehicle (Lidiane *et al.,* 2015).

One of the major limitations of the chopper harvesters was that the chopping process accelerates sugar deterioration because of the easy access of bacteria through abrasion, failure points, and cut surfaces in chopped billets. The harvested billets need to be milled as fast as possible (Anon, 2004).

2.4.3. The manually pushed sugarcane harvester machine

Many manually pushed sugarcane harvester machine was developed and tested in the field. In India small engine driven sugarcane harvester machine was developed and tested for performance. The performance evaluation of the developed sugarcane harvester was compared with the traditional method of harvesting. The developed sugarcane harvester has effective width of 100 cm. It was found that 0.1005 ha/h average effective field capacity at operating speed of 1 km/hr. and 79.42 per cent field efficiency of sugarcane harvester with minimum labour requirements (5 man-h/ha) as compared to the traditional method of harvesting (Tahsin,2018).

And also in India, due to the high cost of the advanced technology of the sugarcane harvester the manually pushed sugarcane was developed. The project aims to design and fabricate small scale sugarcane harvesting machine for sugarcane harvesting to reduce farmer's effort and to increase the output of agricultural products (Siddaling, 2015).

Vahid *et.al*. (2017) developed and fabricated manually pushed sugarcane harvester machine to reduce farmer's effort and to increase production of agricultural goods. Compared to manual harvesting this machine has a capacity to cut canes in faster rate. It is also economical as compared with manual harvesting system.

2.5. Engineering properties of sugarcane

2.5.1. The mechanical property of the sugarcane

The mechanical properties of the plant material significantly influence the performance of the different unit operations in the harvesting machine. The mechanical properties of sugarcane stalk viz., bending resistance; cutting resistance, penetration resistance, and crushing resistance were researched by many researchers over the years.

Some mechanical properties such as rupture force and energy, bio-yield force, bio-yield energy, and deformation at horizontal and vertical loading direction by using a universal testing machine (Oriola *et al*., 2017). Another experiment was performed to determine the different force on sugarcane, the determined force would be 2677 N, 11.15 Nm, 2828 N, 8.92 Nm, and 7.32 mm respectively at vertical loading direction, and 3157 N, 17.83 Nm, 3115 N, 11.43 Nm and 8.41 mm horizontal loading direction for *Saccharum officinarum.* Sugar cane L310 and L820 with average moisture contents of 76.4 and 73.8% wet basis, respectively, were determined. The mean values of shear strength, specific shearing energy, bending strength, and Young's modulus of L310 and L820 varieties were obtained as 4.92 and 5.25 MPa, 53.36, and 57.35 MJ mm^{-2}, 9.58 and 9.20 MPa, and 18.81 and 24.50 MPa, respectively (Hasan *et al.*, 2012).

2.5.2. The physical property of sugarcane

The diameter of sugarcane varies from the bottom to top and this variation depends upon the varieties and climatic condition which prevailed in the growth phase of the sugarcane (Bastian and Shridar, 2014). Two researchers used Rind Hardness was an instrument to determine the hardness of the canes. They set out to produce a sugar cane that would be resistant to the rats, jackals, porcupines, and wild pigs which damage the canes grown by the villagers in the Indian cane growing areas. When conducting the measurements a short piece of sugarcane is placed on the carrier, consisting of two or three internodes in length (Hedley and Chem, 2012).

The studies on the potential of developing sugarcane byproducts based on Indian industries concluded that typical sugar industry processing of 100 tons of sugarcane produces the number of biogases of 30 tons (i.e. 30%) with moisture content in the range of 43-50%, the quantity of molasses of 4 tons (i.e. 4%) and the quantity of filter cake of 3 tons (i.e. 3%) with moisture content in the range of 50- 75% (Sonaje and Kulkarni, 2015).

2.6. Harvesting activities of sugarcane in Ethiopia

All over the country sugarcane harvesting activities were performed manually. In the factory, the sugarcane cutting and harvesting are performed by using a common practice burning down the cane to simplify manual harvesting and avoid possible attacks by insects within the farm. During the transporting of sugarcane, the extent of rollover accidents of the truck tractors has reached an alarming rate and it is incurring huge material and financial losses on the corporation. The researchers studied the technical and non-technical point of view for the possible factors that cause rollover (Ermias Feliche *et al.,* 2017).

2.7. Manual harvesting tools

During manual harvesting, the operators firstly catch the sugarcane with the left or right hand and then strike the bottom part of the sugarcane with one hand. Then, the separated root of sugarcane from the ground was rotated to the top part and then cut the sugarcane top. Then, the body of the sugarcane was dropped to the row and ready to pick with the grab loader machine.

Figure 2. 3. Manual harvesting tools

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Study site description

The sugarcane harvesting machine prototype fabrication and its performance test were conducted in the Wonji Shoa sugar factory Dodota sub-branch workshop and farm field respectively. It was one of the sugar factories in Ethiopia which was found at the Oromia region near Adama City at 25.3 km and from Addis Ababa 110 km. Wonji Sugar factory was the oldest and the pioneer in the history of Ethiopia's sugar industry and start production in 1954. Accordingly, the newly built and modern Wonji Shoa Sugar Factory has currently a design capacity of crushing 6,250 tons of cane a day and producing 174,946 tons of sugar per annum which with further expansion work will reach up to 12,500 productions to 220,700 tons of sugar a year. Its agricultural expansion project was currently being carried out around the areas known as Wakie Tiyo, Welenchiti, and North Dodota areas.

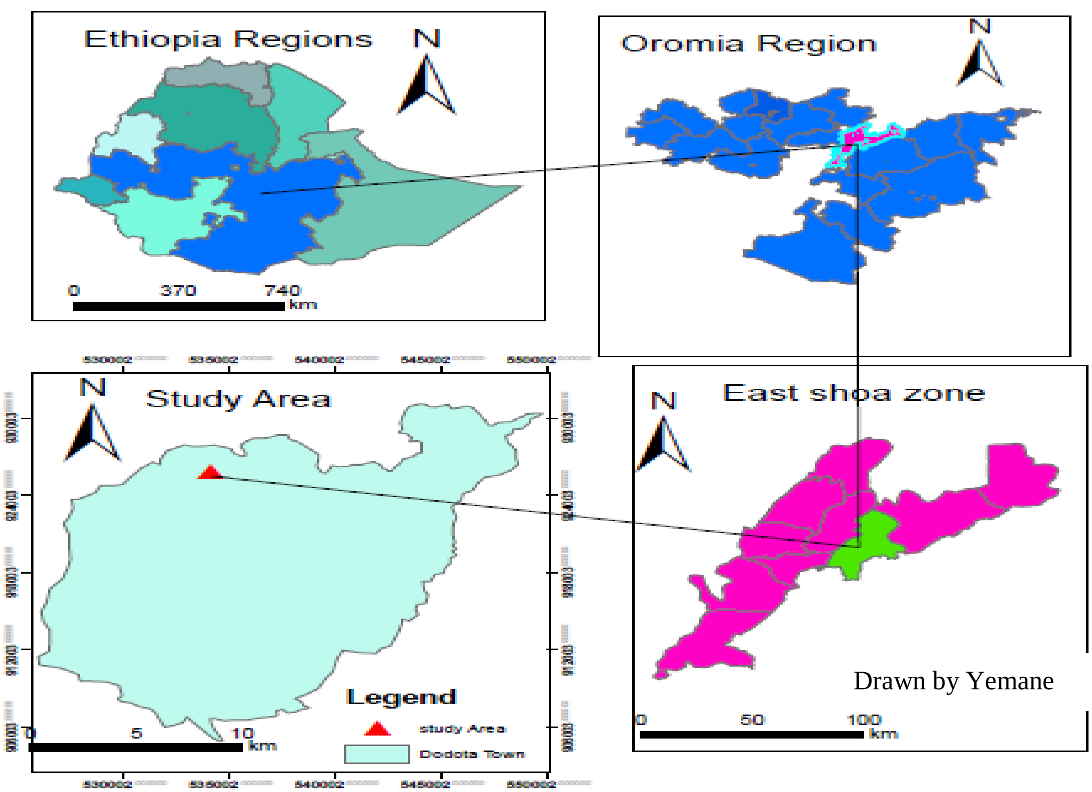

Figure 3. 1. Location map of the study area

3.2. Material selection

From nature, the stem of the sugarcane was harder than other parts of the sugarcane. So the material selection could be related to the strength of the sugarcane stem to minimize and control the bending and breaking off part of the machine during harvesting. During construction, different materials were selected from the store and other related were bought from the market to fulfill the requirements. The materials selected from the store and markets were based on durability, strength, endurance, availability, and cost.

The material designed for sugarcane harvester's machine parts like disc and cutter must be resistant to corrosion and it was made from non-corrosive materials like stainless steel, but some parts like the frame, safety guard were constructed from high thickness flat sheet metal. The shaft was selected from the available store and machined to the optimum required size. The horizontal shaft and wheel shaft have 50 mm diameter and vertical shaft have 30 mm in diameter.

Table 3. 1. Tools and equipment used for harvesting machine development

No	Machine/tool name	Purpose
1.	Drill machine	Making hole
2.	Lathe machine	Threading /finishing /cutting
3.	Grinding machine	Cutting tool
4.	Welding machine	Welding
5.	Steel tape	Measurement of linear distance
6.	Vernier calipers	Measurement of the outer and inner diameter
7.	Hammer	Used to strike an object
8.	Screwdriver	Tighten screw
9.	Spanner	Tighten nut and bolt
10.	Snip	Cutting sheet metal
11.	File	Smooth rough edge

Table 3. 2. Materials and component specifications

No	Components	Quantity	Material and specification
1.	IC engine	1	Five horsepower diesel engine
2.	Discs	2	Made from a steel alloy with bottom and topper cutter having 300 mm in diameter and thickness of 6 mm and 3 mm respectively.
3.	Cutter	6 (for bottom) 4 (for topper)	Made from stainless steel which was connected to each disc The bottom cutter had dimension 90 mm × 80 mm × 50 mm and 3 mm of length, bottom width, top width, and thickness respectively and The Topper cutter had a dimension of 120 mm × 70 mm × 50 mm and 3 mm of length, bottom width, and top width and thickness respectively.
4.	Frame	-	Made from 6 mm thickness flat metal of 800 mm length, 600 mm width, 200 mm height.
5.	Shaft	2	Machined from the mild steel. The horizontal shaft has a dimension of 50 mm diameter and length of 1100 mm. The vertical shaft has a diameter of 30 mm and a length of 1450 mm.
6.	Gear	2	Used to transfer horizontal rotation motion to the vertical shaft (Gearwheel and pinion have 17 and 17 teeth number respectively). Made from a steel alloy.
7.	Bearing	7	Made from chromium alloy steel which was attached to the rotating part to transfer rotation
8.	Gearbox	1	Machined from sheet metal used to cover the gears
9.	Pulley	2	Pulley made from the cast with larger Pulley Ø = 138 mm, smaller Pulley Ø =50 mm
10.	Belt	1	Made from strong plastic material with a total length of 1095.16 mm. Selected from store B-49.
11.	Handle	2	Made from round hollow bar steel used to push the machine
12.	Wheels	3	Made from flat metal with a thickness of 4 mm.

3.3. Design consideration of the machine

In the design of machine components, the working and operational principles were considered. Appropriate design of the cutting mechanism was crucial to successful sugarcane production because it affects energy consumptions, cut quality, and the probability of plugging of the cut stem in the harvester cutting unit. Sugarcane by its nature has a strong stem that needs high energy to cut and allow it to drop on the ground. So the details mechanical design was also given with due attention so that it gave adequate functional rigidity for the design of the machine.

The following design factors that were taken into consideration. The assumption was made during the design of the machine.

- Fabrication of the machine components was considered for periodic servicing.
- The machine was constructed with the use of the availability of local materials to ensure the need for possible replacement of damaged parts that are not expensive.
- The overall cost of the machine was considered based on the LCC of the machine throughout the design stage.
- Physical properties of sugarcane such as diameter and height were considered.
- Machine factors such as strength, stability, rigidity, and whole weight was considered.
- The machine was operated by a human being so considering human daily power requirements by using the following formula (Campbell, 1990). hP = 0.35-0.092 log t; where: t is time in minute. So the power developed by the operators was 0.10-0.13 hP, say 0.11 hP or 80 W for 3-4 continuous work.
- The steady-state power output of human beings must be limited to maximum absorption of oxygen under optimal condition, i.e. 298 to 373 W. For long term work, lasting all day power output for ordinary healthy individuals can produce less than 70-80% as much power i.e. 59 to 112 W (Singh *et al.*,2016).
- Power developed by the worker (men) was taken 0.1hp (0.075 kW) and 0.8 of men power for women workers which were 60 W (Michael, 1987).
- The average level of energy expenditure acceptable for day-long work was considered based on 40% of aerobic capacity which comes to be 0.64 l/min for women workers (Singh *et al.,* 2008).

3.4. Description of machine

The driving mechanism of the machine consists of a motor and transmission units were the pulley-belt system. Horizontal and vertical shafts were machined from common shaft material available and connected with bevel gear. Based on the cost, a mild steel rod with diameter 50 mm and 30 mm was chosen as the preferred choice for both horizontal and vertical shafts respectively and machined to required size. The power was transmitted to the horizontal shaft with the help of a pulley and belt systems. This rotational motion was also transmitted to the vertical shaft with the help of bevel gear which was available in the gearbox. During this, the discs in both top and bottom were rotated horizontal direction to cut the sugarcane.

The distance between the shaft with pulley and power source was determined by the length of the belt selected from or designed. The harvester machine can get the power from the diesel engine motor for cutting the cane. This motor-powered mechanism changed the power from the motor through the belt to the rotational movement of a cutter blade fitted to the shaft.

The discs rotate around its axis with the shaft which was assembled and connected with bevel gears to transfer rotational motion from the horizontal shaft to the vertical shaft. The discs were rotated with 1085 rpm with vertical shafts. The power transmission system consists of pulley belt mechanisms and the diameter of the large pulley on the horizontal shaft was 138 mm and the small pulley on the motor shaft was 50 mm. The belt length was 1095.16 mm.

The frame dimension was 600 mm wide width, 800 mm length, and 200 mm height and made from 6 mm flat metals. The amount of laborer needed to operate the machine was one person. The machines have an overall weight of the 781.26 N.

The machine consists of different parts like frame, cutter, and disc for bottom and topper, horizontal shaft, vertical shaft, gearbox, diesel motor, handle, safety frame, and finally ground wheels. Each part was constructed and assembled step by step to facilitate the construction system. The machine cuts the sugarcane at the bottom and top part. Both cutting units were rotated by gear which was assembled in the gearbox. The below designed and constructed part was assembled and give the 3 models of the machine with different parts.

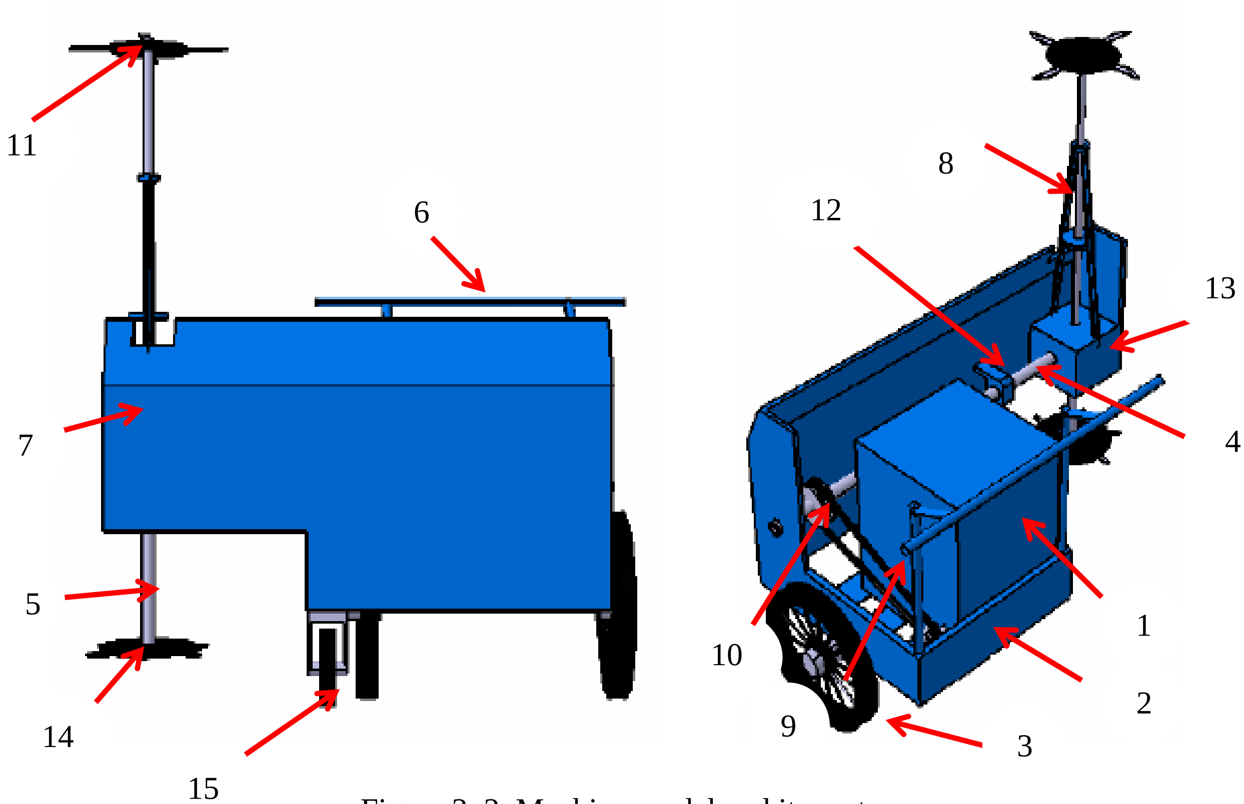

Figure 3. 2. Machine model and its parts

The key component of the machine

1-Motor box	9-belt
2-Frame	10- pulley
3-Large ground Wheel	11-Top cutter disc
4-Horizontal shaft	12-Bearing house
5-Vertical shaft	13-Gearbox
6-Handle	14-Bottom cutter disc
7-Safety frame	15-Balancing wheel
8-The vertical shaft support frame	

3.5. Design of the machine components

3.5.1. Frame

A strong and less weight frame with the desired thickness and according to the row spacing of sugarcane was fabricated to hold the power unit, power transmission, and safety frame. The frame was particularly important in field machines because they must be as light as possible to reduce load to move from one field to another, list of cost, and but yet strong enough to resist the imposed shocks due to the vibration of rotating parts. With a lightweight construction, there was often considerable deflection, and as a rule self-aligning bearings are necessary for rotating parts.

The support frame was the main base of the harvesting machine on which the body was mounted with wheels and other parts. As per the design the parts were cut by a cutting machine and welded with a welding machine for suitable strength. It was constructed by joining the flat sheet metal of size 800 × 600 × 100 mm length, width, and height respectively with a thickness of 6 mm.

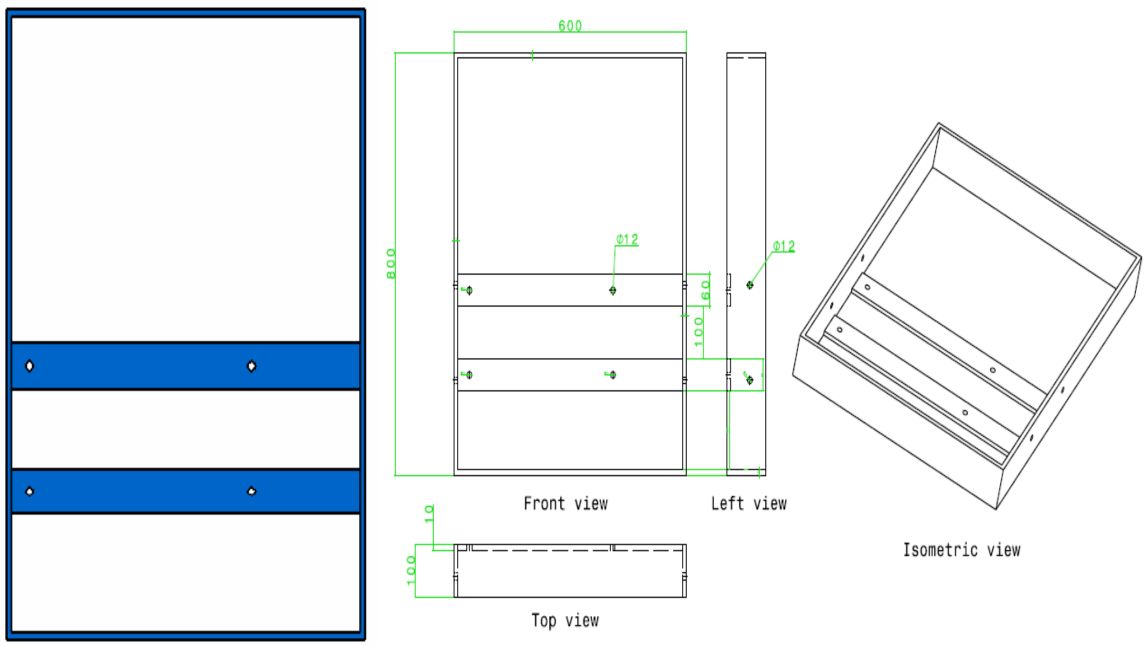

Figure 3. 3. Detail view of the frame

3.5.2. Selection of power

The power required for cutting sugarcane was done by considering the different forces or shear strength. The shear force required to cut the wood was found to be 450 N and the shear force required to cut the sugarcane was 106.57 N (Zode *et al.*, 2015). So, the shear force required to cut sugarcane was less than the wood cutting. The torque could be determined by equation (3.1.) with considering the radius of the disc with cutter and the force required to cut the sugarcane.

$T = Fr$ …………………………………………………………………..……………… 3.1.

Where: T is the torque (Nm), F is the force required to cut the sugarcane (N) and r is the radius of the discs (m).

To minimize the power consumption of sugarcane harvesting the different authors recommended the velocity of the cutter. The optimal rpm to cut the sugarcane was 13.8 m/s, with an oblique angle of 35° and a disc angle of 27° (Gupta and Odour, 2015). Whereas for 0° oblique angle and 8° tilt angle of cutter edge, the recommended the optimal velocity of the cutter to cut the sugarcane was 22 m/s (Lui *et al.*, 2007). From the above research, the recommended velocity for my project was 22 m/s.

Optimal rpm required to cut sugarcane = $\frac{\text{Blade cutting velocity} \times 60}{\text{radius} \times 2\pi}$ ……………………………3.2.

The power required to cut the sugarcane was

$P = \frac{2\pi NT}{60}$ ……………………………………………………………………….…………........3.3.

Where: p is power required to cut the sugarcane; kW, N is speed of cutter which was 1085 rpm; and T is torque of the cutter; Nm

3.5.3. Design of motor box

The motor box was a rectangular shaped structure that was constructed from 2 mm thick sheet metal with a dimension of 400 mm length, 400 mm width, and height 500 mm. It was attached by a nut with the mainframe. It was designed to cover the motor from the external contact and from weather conditions such as rain, cloud and sun. It was attached by the action of the bolt and nut to the main frame and some strengthen materials which were assembled in the main frame.

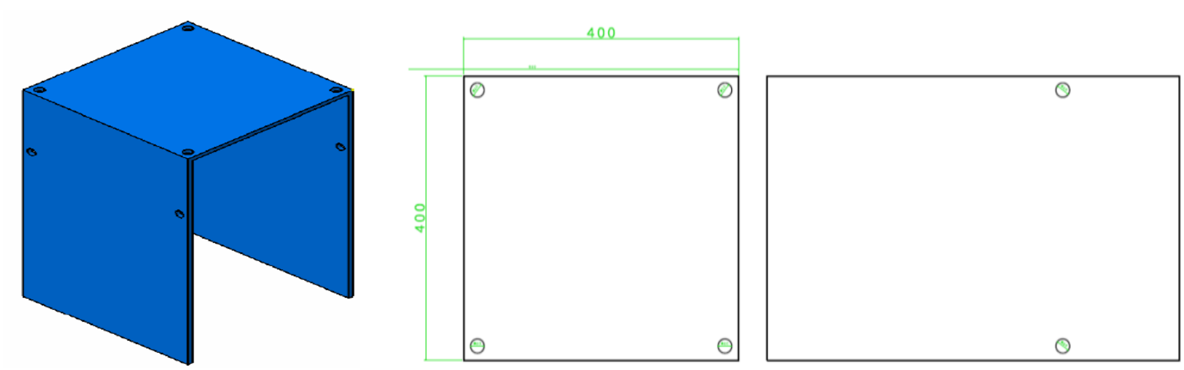

Figure 3. 4. Motor box

3.5.4. Design of the discs with cutter and its kinematic consideration

Cutters commonly used on agricultural field machinery typically perform either, a combination of reciprocating and translating motions, or a combination of rotary and translator motions. In either case, the translator motion, which should be referred to as advance motion, was necessary to transport the implement to its work (Gupta and Odour, 2015). With blades that were rigidly fastened to the rotating shaft, finds the widest application on sugarcane harvesting machines. The bottom and top cutters with the disc was attached to the vertical shaft by the action of bolt and nut.

The rotational motion from the horizontal shaft to the vertical shaft was transferred by the action of gear in the gearbox. The vertical shaft was machined with access to pass through the hole of gear to transfer the rotational motion to the cutting part of the machine. The equal rotational motion was transferred to the cutter for the bottom and top. As the machine travels to harvest the sugarcane, the discs rotate uniformly about its fixed axis from the motor to the horizontal shaft then to the vertical shaft. During this, the sugarcane was beaten firstly by the top cutter which has a longer as compared to the bottom one, and then followed by bottom cutting disc. Gradually the beaten sugarcane was inclined due to the centripetal force which attracts the bottom part of the sugarcane and drops it to the ground to the right side of the operator.

The six cutting blade was attached and distributed uniformly to the bottom disc with a space of 60° and each cutter was constructed with a thickness of 4 mm. The cutting edge was machined with a grinder machine at an angle of 8°. The cutters must be strong enough to overcome the force and minimize the bending during operation. And the disc was connected to the vertical shaft by the action of bolt and nut. The bolt and nut facilitate that if the cutter or disc bent and damaged during operation it was easy to remove the disc and cutter for maintenance.

The top cutter was also attached and distributed on the 300 mm diameter disc at the angle of 90 degrees and it has a length of the 120 mm having a 3 mm thickness. The top cutter was less in weight to minimize the load on the body. When compared with a bottom cutter the top cutter needs less energy so minimizing the number of cutters and the thickness of the disc. They were longer than the bottom cutter to remove the top part of the sugarcane firstly and minimize the load applied due to it. Each cutter was sharp, longer, and light in weight to minimize the load and it must strong enough to overcome the force during harvesting.

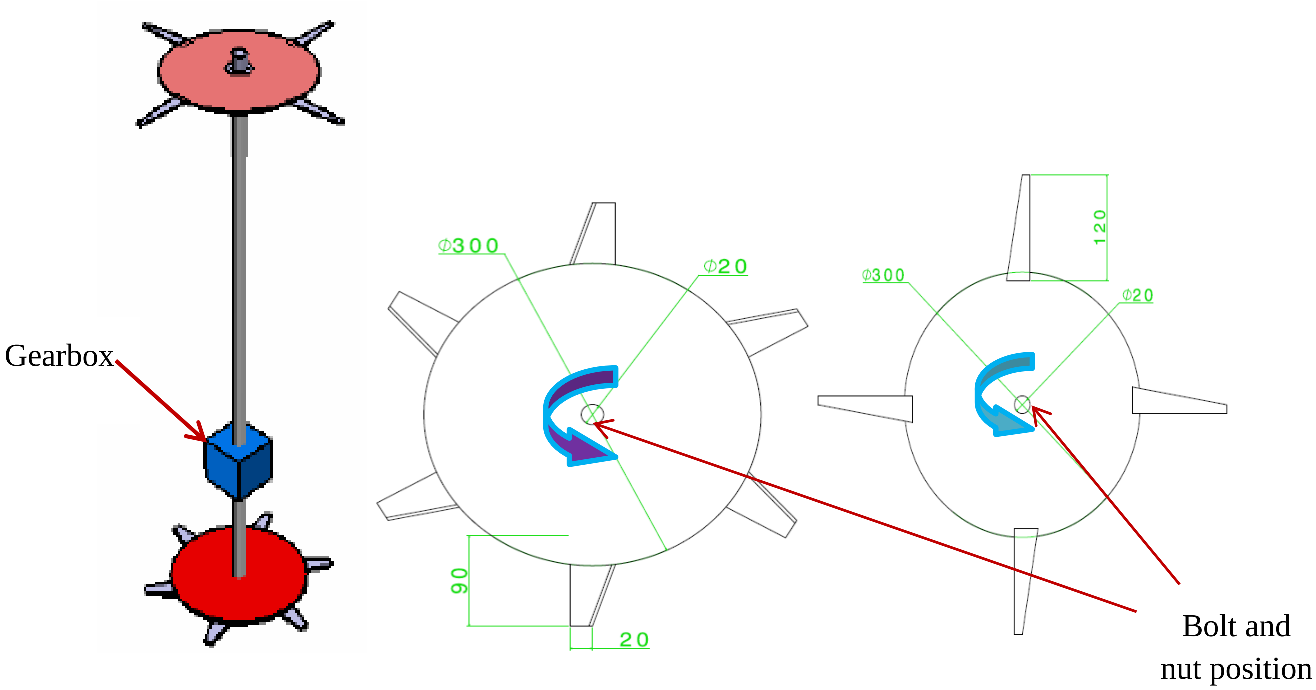

Figure 3. 5. Revolving knife disc with a cutter for the bottom and top disc

The figure above explains the configuration of cutting systems and rotation of the cutter, at an arbitrary time, which should be the initial moment of configuration. At this moment, the origin in which the bolt and nut position, O, coincides with the center of rotation of the cutter.

The following assumptions were made the cutting analysis of the cutter

- The cutting edge was fixed orientation relative to the rotating shaft.
- The blades were uniformly distributed around the periphery of the disc. Thus, if there are n cutting blades in the total circumference of the disc, then the angle was being equal to $\frac{2\pi}{n}$ radians or $\frac{360}{n}$ degrees.
- The cutter rotates in the horizontal plane about its centroid axis with a constant rotational velocity ω (rad/s).

The angular momentum is the tendency of the rotating object to continue with the same angular speed in the same direction and the angular momentum developed at the tip of the cutter was (equation 3.4).

$$M = m \times \omega \times r \quad \ldots 3.4.$$

Where: M is angular momentum ($kg.m^2/s$), m is the mass of discs with cutters (kg), ω is the angular velocity of cutter (rad/s) and r is the radius of discs with cutter (m)

Centripetal force is a force that causes an object to move in the circle at a constant speed because the centripetal acceleration is pointed to toward the center of the circle, then from the Newton second law in vector form was calculated as equation (3.5) (Abdulkadir *et al.*, 2009).

$$F_{cp} = \frac{m \times V^2}{r} \quad \ldots 3.5.$$

Where: Fcp is centripetal force; N, m is mass of disc, Kg, v is linear velocity of disc; m/s and r is radius of disc; m

3.5.5. Selection of pulley

Pulleys were one of the most important power transmission elements, but they require careful design. A pulley reduces these effects with rolling contact between the cable and the machine, but it must be of sufficient size, typically 20 times the cable diameter, to prevent fatiguing of the cable strands. If the power ranges from 1.5 to 15 kW, the diameter was preferred to use a pulley having up to 200 mm diameter and B-belt section (Adarsh *et al.*, 2013).

Table 3. 3. Belt selection criteria

Section belt	Power ranges in KW	Top width, mm	Bottom width, mm	Thicknes s, mm	Weight per meter length in N
B-section	1.5-15	17	9	11	1.98

Source: Khurmi, 2014

The pulley diameter was 138 mm for driven and 50 mm driver, bevel gear teeth number 17 for both driver gear and driven pinion respectively. The coefficient friction and groove angles were 0.3 and 20° respectively. If the power (3.36 KW or 4.9 HP) and rpm (3000) of the engine known from the manufacturer manual and then calculate the torque on the shaft of the engine. The torque on the engine shaft due to a belt calculated as equation 3.6.

$$P = \frac{2\pi NT}{60}; \; T = \frac{Power \times 60}{2\pi N} \quad \ldots 3.6.$$

The velocity of the belt was calculated as equation 3.7.

$$V = \frac{\pi \times d \times N}{60} \quad \ldots 3.7.$$

Where: V is velocity of the belt; m/s, d is diameter of the pulley at the engine; m and N is speed of the motor pulley, rpm

From the speed ratio of the motor shaft to the horizontal shaft, the speed of the horizontal shaft was obtained by the following equation 3.8 (Khurmi and Gupta, 2005).

$N_1D_1 = N_2D_2$...3.8.

Where: N_1 = angular speed of motor shaft

D_1 = diameter of a driving pulley

N_2 = angular speed of the horizontal shaft

D_2 = diameter of the driven pulley

Length of the belt

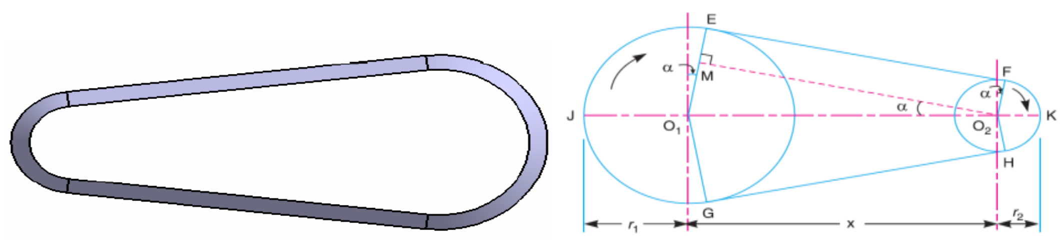

Figure 3. 6. Belt expression

The belt was selected from the store and it has its length. The selected belt was B-49. The length of the belt was determined by the following relation (Khurmi and Gupta, 2005).

$L = 2X + \pi \frac{D_1+D_2}{2}$ …………………..……………………………..……………..……..……3.9.

Where: L = Length of belt, mm;

D_1 = Diameter of driver pulley,

D_2 = Diameter of driven pulley, and

X = Centre to center distance of belt

Centrifugal tension

Since the belt continuously runs over the pulleys, therefore, some centrifugal force is caused, whose effect was to increase the tension on both, tight as well as the slack sides. At lower belt speeds (less than 10 m/s), the centrifugal tension was very small, but at higher belt speeds (more than 10 m/s), its effect was considerable and thus should be taken into account (Khurmi and Gupta, 2005).

$F_{cf} = T_c = mv^2$ ……………………………………………………………………….…………..3.10.

Where: m = mass of the disc, V = speed/velocity of the belt

The input power from the diesel engine motor and the maximum twisting moment developed on the shaft were determined from the input powered as equation 3.11 (Bashir *et al.*, 2013).

$P_{in} = \frac{2\pi N_1 T}{60}$……………………………………………………………………………………….3.11.

Where: P_{in} is input power from motor, N_1 is angular speed of the motor shaft, and T is the twisting moment of the motor shaft

The output power transmitted through the belt T_1 and T_2 of the harvester machine was determined as equation 3.12 (Bashir *et al.*, 2013).

$P_d = \frac{2\pi N_2 T}{60}$……………………………………………………………………………………..3.12.

Where: P_d = output power required to cut the sugarcane, W

T = twisting moment developed on the horizontal shaft

N_2 = angular speed of the horizontal shaft

The belt efficiency to transmit power from the power source to the horizontal rotating shaft was determined as equation 3.13 (Bashir *et al.*, 2013).

Power transmitted over the belt (%) = $\frac{\text{Output power}}{\text{input power}} \times 100$ ………………………………...3.13.

The total driving force of the harvester was determined by the equation as (3.14, 3.15, and 3.16) (Khurmi and Gupta, 2005).

$F = (T_1 - T_2)$……………………………………………………………………………… 3.14.

$T_1 = 3T_c$ ………………………………………………………………………………………3.15.

$F = (3T_c - T_2)$ …………………………………………………………………………… 3.16.

Where: F is force required to drive the machine (N), T_1 is Tension on the tight side of the belt (N), T_2 is Tension on the slack side of the belt (N) and T_c is centrifugal force (N) and T_1 is $3T_C$.

But the value of the driving force was determined from the output force as shown in the equation (3.17) (Bashir *et al.*, 2013).

P = Fv ……………………………………………………………………………………… 3.17.

Where: p = output (transmitted) power through belt T_1 andT_2

F = force required to drive

v = velocity of the belt

$T_c = mv^2$= N…...3.18.

F= $(3T_c - T_2)$ and T1 = 3TC …………………………………….……..………………. 3.19.

Power transmitted per belt

P = $(T_1\text{-}T_2) \times V$ ………………………………………………..…….….……….….….3.20.

The number of belts required = $\frac{\text{Total power transmitted (kW)}}{\text{Power transmitted per belt (kW)}}$ ……………...…………..….3.21.

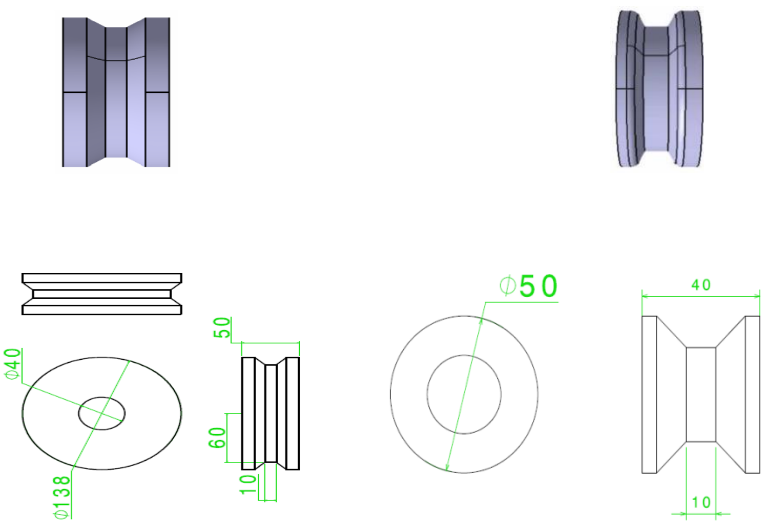

Figure 3. 7. Pulley and its detail view

3.5.6. Design of shaft

The shaft used for this machine was subjected to two types of forces namely twisting moment and bending moment. The shaft was expected to be subjected to both torsion and bending moment. This may be due to the rotational effect of the shaft during the rotational motion of the machine. The failure of the shaft was likely to be in shear stress and the design considered this fact. Loading, the diameter was obtained using the ASME code equation 3.22 (Khurmi and Gupta, 2005).

$d^3 = \frac{16}{Ss}\sqrt{(Kb \times Mb)^2 + (Kt \times Mt)^2}$ ………………………………………….…………..3.22.

Where: d is diameter of the shaft; mm, Mt is torsional moment; Nm, Mb is bending moment; Nm, Kb is combined shock and fatigue factor applied to bend moment, Kt is combined shock and fatigue factor applied to torsional moment and Ss is allowable stress; MN/m^2

According to ASME code for rotating shafts, when the load was suddenly applied with minor shock, the values of Kb = 1.2 to 2.0 and Kt = 1.0 to 1.50 was used. Furthermore, it was noted that for shaft without keyway, the allowable stress Ss must be 55 MN/m^2 and for the shaft with the keyway the allowable stress Ss should not exceed 40 MN/m^2 (Khurmi and Gupta, 2005).

Table 3. 4. ASME code for shaft design

Type of load	Stationery shaft		Rotating shaft	
	Kb	Kt	Kt	Kt
Gradually applied load	1	1	1.5	1
Suddenly applied load, minor shock	1.5-2	1.5-2	1.5-2	1-1.5
Suddenly applied load, heavy shock	-	-	2-3	1.5-3

Source: (Khurmi and Gupta, 2005).

The torsional moment (Mt) on the shaft was 15.98Nm, then the Shaft subjected to bending moment only then the maximum bending moment on the shaft was determined from the bending diagram as equation 3.24 (Khurmi and Gupta, 2005).

The bending stress of the horizontal shaft was calculated by using the following equation as

$$\tau = \frac{16T(NM)}{\pi d0^3(M) \times (1-k^4)} \quad \ldots\ldots 3.23.$$

Where: τ = bending stress due to torque

T= Torque on shaft; NM

K = ratio of the outer and inner diameter of the shaft (k=0 for a solid shaft because inner diameter was zero).

d_o= outer diameter of shaft

d_i = inner diameter of shaft

The bending moment of the horizontal shaft was calculated as equation 3.24

$$Mb= \frac{\pi\tau \times d^3}{32} \quad \ldots\ldots 3.24.$$

Therefore, the selected shaft as standard to withstand the load which was delivered from the motor and can resist the different force during the operation of the machine.

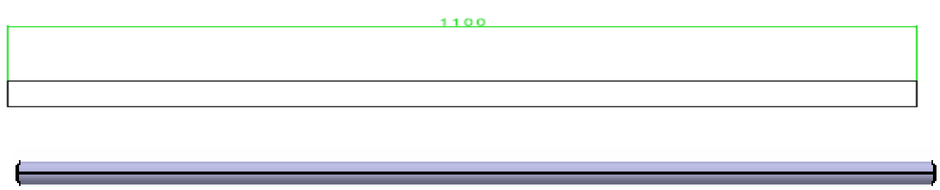

Figure 3. 8. Shaft design

Vertical Forces Distribution on the Shaft

The vertical load diagram on the driven pulley shaft was as shown below. The total weight on the horizontal shaft was calculated by summing all weight which was imposed on it. The weight on the shaft was a pulley, bottom cutter, bottom disc, top cutter, top disc, gears, and vertical shaft weights.

The forces distributions at two force support R_a and R_b were not equal which means 1/3 for R_a and 2/3 for R_b because the forces at the R_b were greater and 2/3 length of the shaft was supported by pivot Rb. The total weight on the shaft (W_S) were

The weight for each support pivot was described as follows.

W_A = weight of the pulley + half of the horizontal shaft

W_B = half weight of the horizontal shaft + vertical shaft weight + gears weight + top cutter weight + top disc + bottom disc + bottom cutter

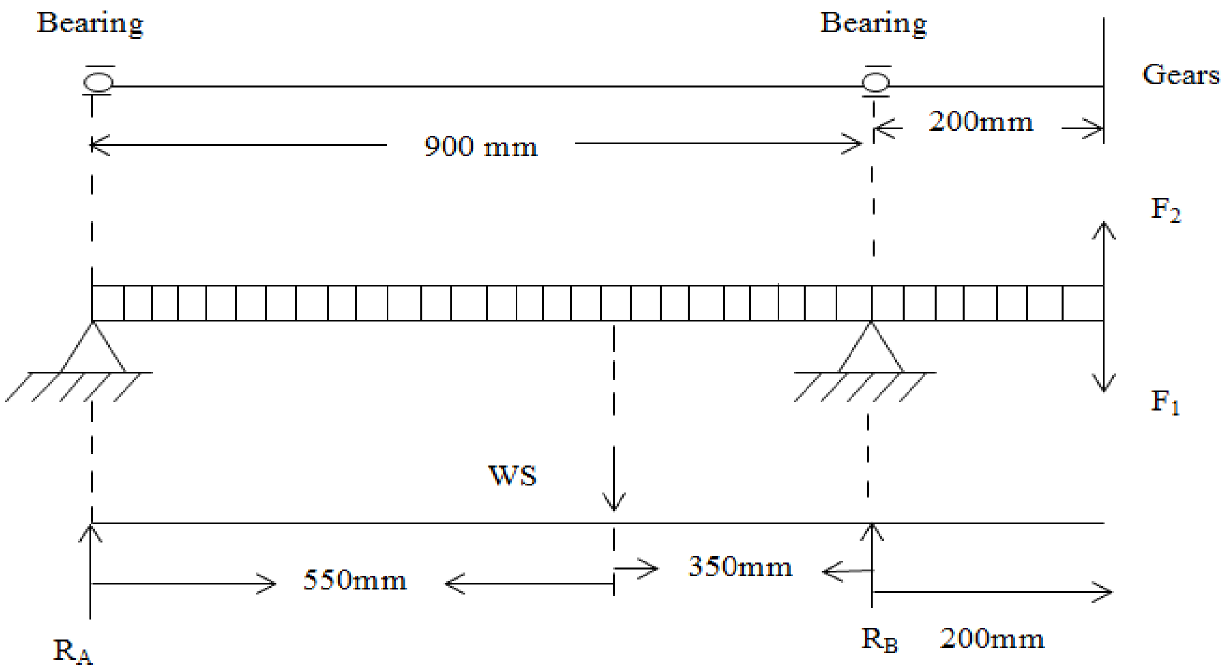

Figure 3. 9. Vertical forces distribution on the shaft

Where: F_1 = forces on the bottom disc and cutter

F_2 = forces on the top disc and cutter

To calculate unknown variables R_A and R_B let me calculate the moment at each point by using equilibrium equations. The clockwise direction was negative and the clockwise direction positive.

$\sum M_A = 0$ ……………………………………………………………………………………3.25.

$(-W_S \times 0.55m) - (F_1 \times 1.1m) + (R_B \times 0.9) + (F_2 \times 1.1m) = 0$

$\sum M_B = 0$……………………………………………………………………………………3.26.

$(-R_A \times 0.9m) + (W_S \times 0.35) + (F_2 \times 0.2) - (F_1 \times 0.2m) = 0$

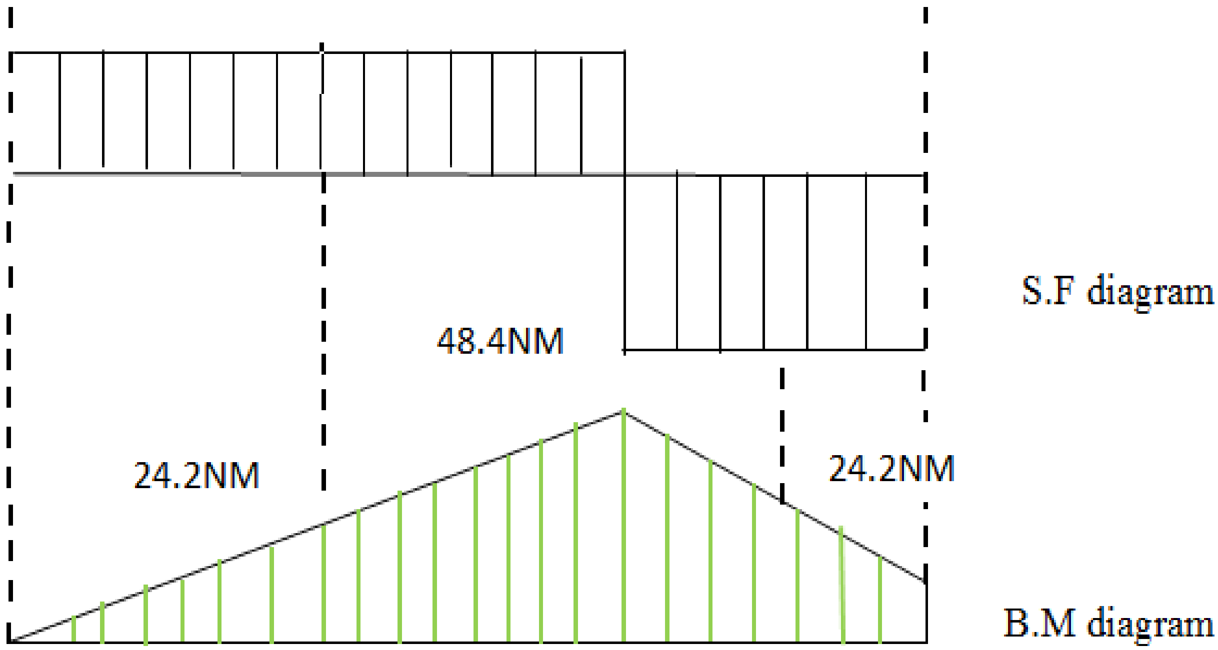

Figure 3. 10. Shear force and bending moment diagram

3.5.7. Design of bevel gear

A bevel gear is shaped like a section of a cone and is primarily used to transfer power between intersecting shafts at right angles. The teeth of a bevel gear may be straight or spiral.

Table 3. 5. The minimum numbers of teeth to prevent undercut

Pressure angle	Combination of number of teeth			$\frac{z1}{z2}$		
14.5°	29/over 29	28/over 29	27/over 31	26/over 35	25/over 40	24/over 54
20°	16/over 16	15/over 17	14/over 20	13/over 30	-	-
25°	13/over 13					

Source: Element of metric gear technology, Kohara Gear Company of Japan

The pulley was mounted to the output shaft of the engine and through the belt drives the power was transferred to the horizontal shaft of the cutter assembly. Bevel gear was used to transfer the power from horizontal to the vertical shaft of the cutter assembly. So the 4.6 hP engine running at 3000 rpm was used as the prime mover. The horizontal and vertical shaft has 1085 rpm.

Where: Z_1= bevel gear, driver pinion

Z_2 = driven gear, driven pinion

N_1 = speed at horizontal shaft

N_2 = speed at vertical shaft and cutter

The speed transmitted to N_2 was calculated by the following relation

$$\frac{Z1}{Z2} = \frac{N2}{N1} \quad \text{......3.27.}$$

Hence the N_2 has 1085 rpm and the speed of the cutter which was connected to the vertical shaft would be 1085 rpm.

The velocity ratio or input gear ratio will be

$$I = \frac{Z2}{Z1} \quad \text{......3.28.}$$

The module for my design was 3 because of the pitch diameter of the gear and the number of teeth. The module is unit less to be determined from the AGMA standard table for tooth form. The module m is used as metric standard input and relates the number of teeth with pitch diameter for pinion and gear by the following formula. Bevel gear teeth were located along with the elements of the cone and dependent on the ratio of several teeth in the two mating gears (Mott, 2004).

The following table indicates the parameters used to design the bevel gears. Each parameter was considered by using gear design specifications.

Table 3. 6. Gear design elements and values

Parameter	Formulas
Number of teeth	$Z_1 = 17$
	$Z_2 = 17$
Module (m)	3
Pitch diameter d_1 and d_2	$d_1 = m \times Z_1$
	$d_2 = m \times Z_2$

Pitch cone angle for pinion and gear [degree]	$\delta_1 = \tan^{-1}(\frac{\sin\Sigma}{\frac{Z1}{Z2}+\cos\Sigma})$
	$\delta_2 = \sum - \delta_1$
Outer cone distance (R_e) [mm]	$\frac{D2}{2\sin\delta2}$
Face width or tooth flank width, b [mm]	$\frac{R_e}{3}$or 10m
Mean cone distance (R_m) [mm]	R_m = Re – 0.5 b
Addendum (h_a) [mm]	h_a = 1.00m
Dedendum (h_f) [mm]	h_f = 1.188m
Working depth (h_w) [mm]	2m
Whole depth (h_l) [mm]	h_l = 2.188m+0.05
Clearance (c) [mm]	C= 0.188m+0.05
Dedendum angle (θ_f) [degree]	$\theta_f = \tan^{-1}(\frac{hf}{Re})$
Addendum angle (θ_a) [degree]	$\theta_a = \tan^{-1}(\frac{ha}{Re})$
Outer cone angle for pinion and gear (δa_1 and δa_2)	$\delta a_1 = \delta_1 + \theta a$
[degree]	$\delta a_2 = \delta_2 + \theta a$
Root cone angle for pinion and gear (δf_1 and δf_2) [degree]	$\delta f_1 = \delta_1 - \theta f$
	$\delta f_2 = \delta_2 - \theta f$
Outside diameter for pinion and gear (da_1 and da_2) [mm]	$da_1 = d_1 + 2ha\, Cos\delta_1$
	$da_2 = d_2 + 2ha\, Cos\delta_2$

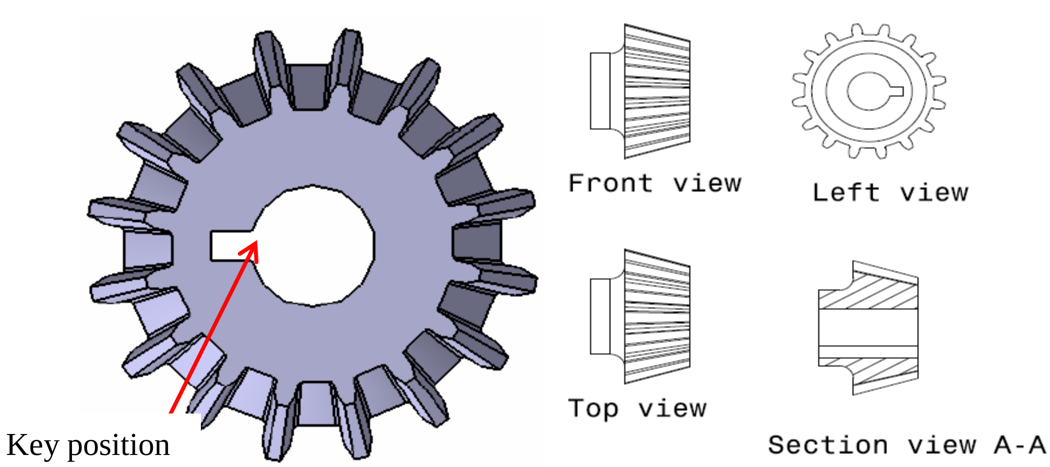

Figure 3. 11. Bevel gear views

3.5.8. Design of safety frame

To prevent the possibility of shaft damage, and contact with other external material most probably the sugarcane while harvesting or operating the machine, the safety frame was designed to horizontal shaft length and a vertical shaft having a length of 1100 mm and 450 mm respectively. And also have a bearing house in the left and right side positions to facilitate the rotation of the horizontal shaft. There was also a bearing and bearing house for the vertical shaft just to keep the weight of the shaft, cutter, and disc together.

The safety frame was also attached to the gearbox to facilitate the strength of the machine components. The frame was manufactured from strong materials and low weight to minimize the load of the machines. The safety frame was attached to the frame of the machine the action of welding.

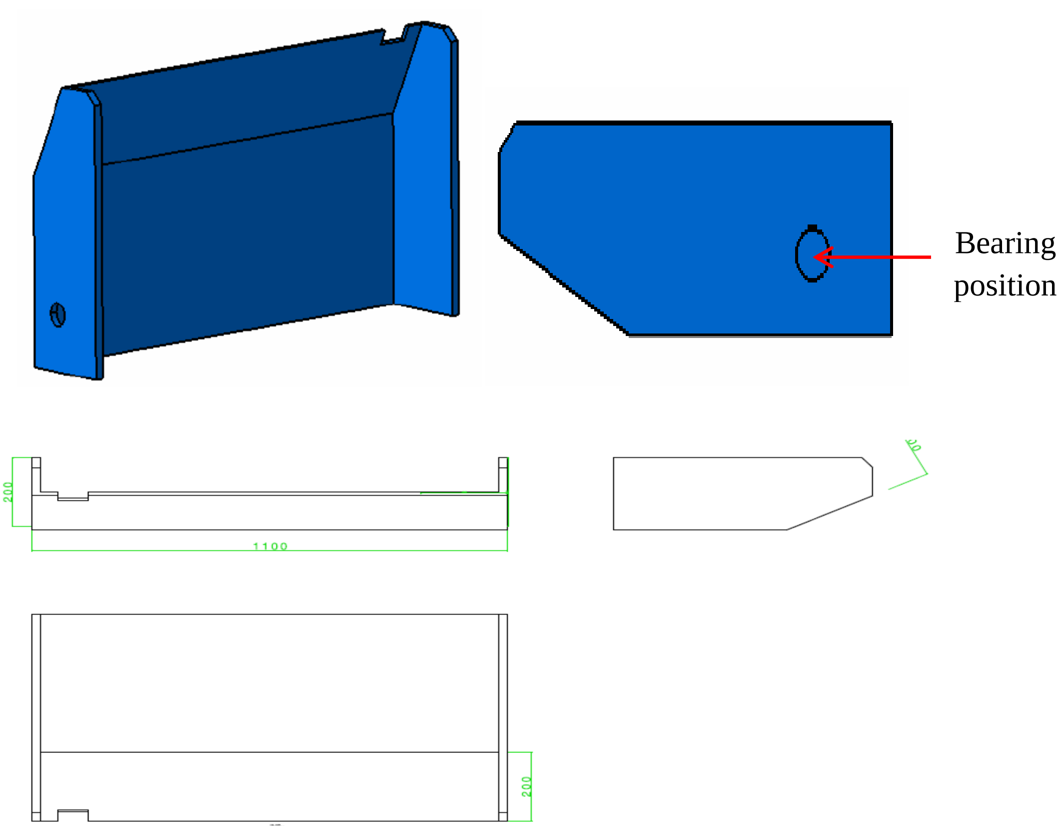

Figure 3. 12. Safety frame views

3.5.9. Design of wheels

Wheels are the circular block of hard metal which was durable and can carry the load that was imposed over it. It has a circular hole that was bored in which the shaft rotates when a force was applied by the operators to the wheels about its axis. Metal welded wheels were moved faster than other types of material due to their weight and the material property (Rayja *et al.*, 2019). The ground wheel diameter varies from 200 to 600 mm; based on which the suitability diameter was selected. A provision was made on the tool frame to adjust handle height and working tool depth. The design of manual harvesters was based on the draft and power required to operate the tool (Chethan and Krishnan, 2017).

The two back wheels were 600 mm diameter, 12 mm width, and 4 mm thickness and its shaft have 820 mm length with a diameter of 50 mm. The support wheel was constructed for the case of balancing and minimizing the direct contact of the blade with the ground; the gap between the wheel and the cutter was 150 mm.

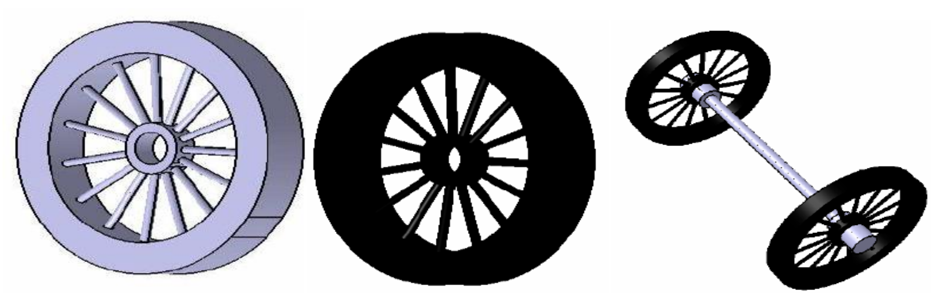

Figure 3. 13. Back wheel views

In front of the machine, there was a small wheel constructed in front of the right side of the wheel to support the load and balancing system. It was 250 mm in diameter with a 4 mm thickness.

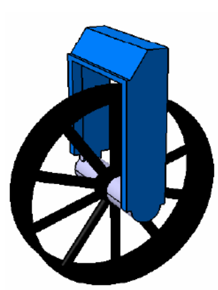

Figure 3. 14. Front-wheel views

3.5.10. Design of handle

During handle design there was different parameter; size, shape, surface, security, stiffness, siting, surroundings, the skill of the operator, and sensing features should be considered (Patkin, 2001). The other factor was the height of the handle hold; which would not be the same for all people. A height that was appropriate for a male may not be a comfort for a female. In this case, the operator of each may bend or stoop and the female would try to reach up above her limited height. Handhold height system that offers continuous vertical handles that can be grasped anywhere along their length or a series of handholds at different heights.

An understanding of force exertions was of immense importance while designing a pushing or pulling task. Existing studies have principally been concerned with static tasks despite the knowledge that most agricultural activities are dynamic and involve overexertion of the muscle-skeletal system. Seven percent of low back injuries were associated with slipping/tripping accidents during pulling or pushing operation (Snook, 1978). The fact to be considered was that harvesting operation is dynamic and associated with a higher risk of injury. Operators were able to contact handholds as near as safely possible to the outer edge of a cart, avoiding crushing injuries, but providing ample leverage for turning and positioning. For maximum power in an adult male, it should be 3 or 4 cm. in diameter (Yadav and Pund, 2007).

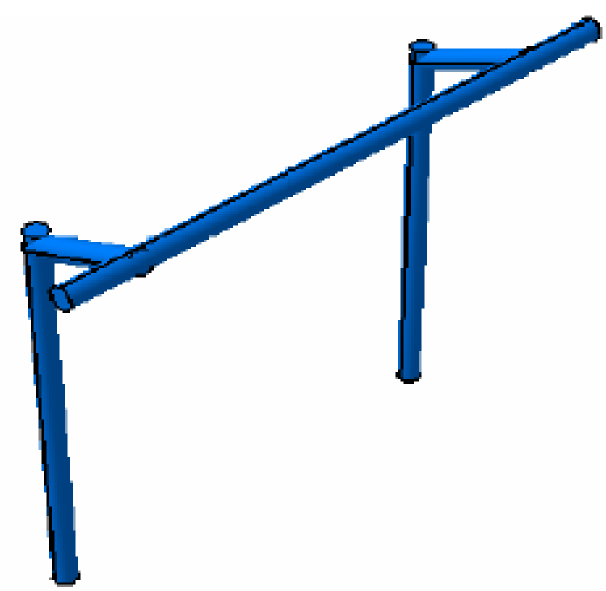

Figure 3. 15. Handle

3.6. Weight Determination of harvester components

In order to estimate the loads on each and every component parts of the prototype planter, it was necessary to estimate weight of all component parts. The frame, discs, cutter, shaft, wheel and safety frame of the harvester were calculated by using appropriate equations.

3.6.1. Weight of the frame

The high thickness sheet metal was used in the construction of the harvester frame. The weight of the frame was calculated as follows.

$A_{FM} = L_{FM} \times$ Width of the frame ………………………………………………………3.29.

The volume of frame material can be computed using the following equations (ITSI-SU, 2011);

V_{FM} = Area × thickness …………………….…….………………………………..3.30.

Mass of the frame was computed using the following equations (ITSI-SU, 2011);

$M_{FM} = V_{FM} \times \rho_{FM}$……………………………………………………………………………………...3.31.

Weight of frame material can be computed using the following equations (Gat, Uri, 1988);

$W_{FM} = M_{FM} \times g$ …………………………………………………………………………………...3.32.

Where: L_{FM} = Length of the frame material

V_{FM} = Volume of the frame material

ρ_{FM} = density of the frame material

M_{FM} = Mass of the frame material

W_{FM} = Weight of the frame material

3.6.2. Weight of the cutters for both top and bottom

The weight of the cutter was calculated by considering two parameters which was rectangular and triangular shape. Weight of bottom cutter can be computed using the following equations (Gat, Uri, 1988);

$W_{BC} = V_{BC} \times g \times \rho_{BC}$ ……………………………………………………………………3.33.

Weight of top cutter can be computed using the following equations (Gat, Uri, 1988);

$W_{TC} = M_{TC} \times g \times \rho_{TC}$ ……………………………………………………………………3.34.

Where: W_{BC} = weight of the bottom cutter

M_{BC} = Mass of the bottom cutter

V_{BC}= volume of the bottom cutter

ρ_{BC} = density of the disc material for bottom cutter

W_{TC} = weight of the top cutter

M_{TC} = Mass of the top cutter

V_{TC}= volume of the top cutter

ρ_{TC} = density of the disc material for top cutter

3.6.3. The weight of the top and bottom disc

The bottom disc area was by using the following equation (Math.com, 2012);

$A_{BD} = \pi r^2$ ……………………………………………………………………………3.35.

The volume of the disc was also calculated as (ITSI-SU, 2011);

$V_{BD} = A_{BD} \times$ Thickness of the disc ……………………………………………………….3.36.

The Mass of the disc was determined by the equation (ITSI-SU, 2011);

$M_{BD} = V_{BD} \times 7860 \frac{kg}{m^3}$

The weight of the disc was calculated by using the following equation (Gat, Uri, 1988);

$W_{BD} = M_{BD} \times g$ …………………………………………………………………………3.37.

The top disc area was by using the following equation (Math.com, 2012);

$A_{TD} = \pi r^2$ …………………………………………………………………………….3.38.

The volume of the disc was also calculated as (ITSI-SU, 2011);

$V_{TD} = A_{TD} \times$ Thickness of the disc ……………………………………………………..3.39.

The Mass of the disc was determined by the equation (ITSI-SU, 2011);

$M_{TD} = V_{TD} \times 7860 \frac{kg}{m^3}$………………………………………………………................3.40.

The weight of the disc was calculated by using the following equation (Gat, Uri, 1988);

$W_{TD} = M_{TD} \times g$ ………………………………………………………………………….3.41.

Where: A_{BD} = Area of the bottom disc

V_{BD} = volume of the bottom disc

M_{BD} = Mass of the bottom disc

W_{BD} = weight of the bottom disc

A_{TD} = Area of the top disc

V_{TD} = Volume of the top disc

M_{TD} = Mass of the top disc

W_{TD} = Weight of the top disc

3.6.4. Weight of safety frame

The safety frame was also classified to two shapes which was rectangular and triangular shape to determine the weight.

$V_{SF} = A_{SF} \times$ thickness of safety frame ………………………………………………..3.42.

The Mass of the safety frame was determined by the equation (ITSI-SU, 2011);

$M_{SF} = V_{SF} \times 7860 \frac{kg}{m^3}$ ……………………………………………………………….3.43.

The weight of the disc was calculated by using the following equation (Gat, Uri, 1988);

$W_{SF} = M_{SF} \times g$ …………………………………………………………………………….3.44.

Where: A_{SF}= area of the safety frame

V_{SF} = volume of the safety frame

M_{SF} = mass of the safety frame

W_{SF} = weight of the safety frame

3.6.5. Weight of motor cover

The motor covering shape was rectangular shaped sheet metal. The area of the metering shaft was estimated as follows (Math.com, 2012). The mass of the motor cover was estimated using the following equations (ITSI-SU, 2011).

$M_{MC} = V_{MC} \times \rho_{MC}$ ....3.45.

The weight of the motor cover was calculated as using equation following (Gat, Uri, 1988);

$W_{MC} = M_{MC} \times g$ ……………………………………………………………………………3.46.

Where: V_{MC} = Volume of the motor cover

M_{MC} =Mass of the motor cover

W_{MC} = Weight of the motor cover

3.6.6. Weight of the shaft

The shaft used in this project was three; horizontal shaft, and vertical shaft. So the area, mass, volume and weight was calculated as follows. The area of the metering shaft was estimated as follows (Math.com, 2012);

$A_{sh} = \frac{\pi D^2}{4}$ ……………………………………………………………………………………..3.47.

The volume of the horizontal shaft was estimated using the following equations (ITSI-SU, 2011);

$V_{sh} = A_{sh} \times L_{sh}$ ……………………………………………………………….……………3.48.

The mass of the horizontal shaft was estimated using the following equations (ITSI-SU, 2011);

$M_{SH} = V_{sh} \times \rho_{sh}$ ………………………………………………………………………...3.49.

The weight of the horizontal shaft was calculated as using equation following (Gat, Uri, 1988);

$W_{sh} = Msh \times g$ ………………………………………………………………….……..3.50.

Area of the vertical shaft was also calculated as (Math.com, 2012);

$A_{sh} = \frac{\pi D^2}{4}$ …………………………………………………………………….……3.51.

The volume of the vertical shaft was estimated using the following equations (ITSI-SU, 2011);

$V_{sh} = A_{sh} \times L_{sh}$ …………………………………………………….………………..3.52.

The mass of the vertical shaft was estimated using the following equations (ITSI-SU, 2011);

$M_{SH} = V_{sh} \times \rho_{sh}$ ……………………………………………………………………………3.53.

The weight of the vertical shaft was calculated as using equation following (Gat, Uri, 1988);

$Wsh = Msh \times g$ ……………………………………….…………………………3.54.

Where: A_{SH} = Area of the shaft

V_{SH} = volume of the shaft

M_{SH} = Mass of the shaft

W_{SH} = weight of the shaft

g= acceleration due to gravity (m/s^2)

3.6.7. Wight of the pulley

The area of the pulley was calculated by considering the shape and dimension during design. The volume of the pulley on the horizontal shaft was calculated as (ITSI-SU, 2011).

$$V_P = ((\pi r_1 - \pi r_2) \times t) - \left(\frac{1}{2}\, a \times b \times h\right) + (a \times b \times h) \quad \ldots 3.55.$$

The mass of the pulley was estimated using the following equations (ITSI-SU, 2011);

$$M_P = V_P \times \rho_P \quad \ldots 3.56.$$

The weight of the pulley was calculated as using equation following (Gat, Uri, 1988);

$$W_P = M_{sh} \times g \quad \ldots 3.57.$$

Where: V_P = Volume of the pulley

M_P = Mass of the pulley

ρ_P = Density of the pulley material

W_P =Weight of the pulley

3.6.8. Weight of the handle

The area of handle was estimated as follows (Math.com, 2012);

$$A_H = \frac{\pi D^2 - d^2}{4} \quad \ldots 3.58.$$

The volume of the handle was estimated using the following equations (ITSI-SU, 2011);

$$V_H = A_H \times L_H \quad \ldots 3.59.$$

The mass of the handle was estimated using the following equations (ITSI-SU, 2011);

$$M_H = V_H \times \rho_H \quad \ldots 3.60.$$

The weight of the handle was calculated as using equation following (Gat, Uri, 1988);

$$W_H = Msh \times g \quad \ldots 3.61.$$

Where: A_H = Area of the handle

V_H = Volume of the hand

M_H = Mass of the handle

W_H = Weight of the handle

3.7. Estimation of Force Required Driving the harvester

A rolling resistance force (F), which is assumed to act horizontal at the wheel and ground interface or ground and wheel contact patch, was estimated using Eq. (3.30) (Reece,2002).

$$F = (CR + i) \times N \qquad \text{3.62.}$$

$$F = \left(\left(\frac{z}{d}\right)^{0.5} + i\right) \times N$$

Where: - CR = coefficient of rolling resistance

d = wheel diameter, 600 mm

z = maximum wheel sinkage depth (on a soft surface z = 0.05d)

N = weight of the planter on each wheel,

i = gradient of the ground, let i = 5%

3.8. Torque on the ground wheel

The torque on the ground wheel was calculated by using the following formula (Sharma and Mukesh, 2010).

$$T = F\left(\frac{d}{2}\right) \qquad \text{3.63.}$$

Where: d= is the diameter of the wheel

F is driving force

3.9. Fabrication of machine

The software drawing was developed, fabricated, and the five horsepower motors were assembled in the proper position over the frame. The different component of the harvesting machine parts mentioned in previously described subheadings was fabricated step by step by considering their position and design and assembled in the workshop of Wonji Shoa sugar factory. The bevel gear, horizontal and vertical shaft, blade and cutter, frame, and safety frame and the handle was fabricated from selected material with their operational property in the sugarcane factory. The entire supporting frame and safety frame was marked and cut, then joined by welding, and screwing according to functional requirement. The cutter and disc were selected and cut with the machine and then welded with their appropriate position.

Figure 3. 16. Machine model and construction of machine in the shop

3.10. Wonji Shoa sugar factory harvesting system

To harvest the sugarcane the laborers were selected and collected from the whole of Ethiopia by the announcement and any volunteer peoples come and participate in the factory to sustain the daily income. In the factory, there was a different cutting stage which means after planting and cutting with different year gaps. For each cutting stage and years, the payment per row was different.

Paying system of the sugar factory

In the factory, the manual laborers paying system was different for each type of planting and years which means age of the sugarcane. For each cutting system and age of the sugarcane, the payment per 100 meters per row was different.

Table 3. 7. Cutting and paying system in the field of Wonji Shoa sugar factory

Field type	Cutting type	Years	Length of row	Birr per 100 m row
Planted field	-	1st year	100 meter	50.13
	-	2nd year	100 meter	62.14
Cut field	1st cutting	1st year	100 meter	46.16
		2nd year	100 meter	51.38
	2nd cutting	1st year	100 meter	45.86

	2nd year	100 meter	51.38
3rd cutting	1st year	100 meter	42.85
	2nd year	100 meter	45.06
4th cutting	1st year	100 meter	42.85
	2nd year	100 meter	45.06
5th cutting	1st year	100 meter	41.77
	2nd year	100 meter	44.28

The number of people assigned in one row of sugarcane to harvest was one. The time required to finish 100 meters of sugarcane was averagely about 3:45 and 5 hours averagely for men and women respectively.

Ten laborers were interviewed about the manual harvesting activities conducted in the field and gave the following yes or no questions. From ten, eight were male and two of them were females. The (table 3.10.) describes about the results collected from the field and the disadvantage and advantage of the manual harvesting activities.

Table 3. 8. Survey on strength and weakness of manually harvesting of cane

S. No	Parameters and Total number of respondents (10)	Number of responses	
		Yes	No
1.	Time and energy-consuming	10	-
2.	Injuries and pain	10	-
3.	Comfortable	1	9
4.	Expose for others disease	1	9
5.	Are you using PPE	2	8
6.	Hard to cut the cane stem	8	2
7.	Increase household income	6	4

3.11. Performance evaluation of mechanical harvesting machine

The developed machine was tested in the laboratory (without load) and in the field (with load). Each performance testing was conducted in the Wonji Shoa sugar factory workshop and farm field.

3.11.1. Laboratory test (without load)

In the laboratory test visual observations and specifications of the machine components and parts were checked for weather the machine was in correct position or not.

3.11.1.1. Visual observations

First, the machine was set on the level area of the workshop and observing the operational condition. In this test observing moving and rotating part, detecting the sound and any other factors such as vibration and shock.

3.11.1.2. Specifications

In this test, the measurement was conducted to check the assembled and constructed part of the machine carefully. Check whether the machine part was correct with designed specifications and on their positions. Some parts of the machine was measured and checked during laboratory test.

3.11.2. Field test

During field test, the different parameters was recorded, measured and compared with in different time intervals which was after 30 minute, after 1 hours, after 1:30 hours, after 2 hours, after 2:30 hours and after 3:00 hours of the operations. The physical property of the sugarcane, cut height above the ground, effective cut width, and area covered, field efficiency, field capacity, and pulse rate of the operators was measured and compared.

3.11.2.1. Diameter of the sugarcane

The diameter of the sugarcane was measured from the harvested fields. The bottom, middle, and top diameter of the sugarcane were measured by using Vernier caliper in both harvesting systems. The ten sugarcanes were randomly selected from the harvested field and measured for diameters and identified for mean diameters.

3.11.2.2. Height of the sugarcane

The height of the sugarcane from the mechanical harvested field was measured, recorded, and compared. Ten sugarcanes were selected randomly and measured for height by using measuring tape.

3.11.2.3. Cut height above the ground

From the harvested field, the height of the cut above ground was taken randomly. From field, five roots left of the sugarcane were recorded and measured. The height of the cut was measured by using the measuring tape (see Appendix B). This height of the cut of the machine was compared with in each time intervals to determine the performance of the machine.

The time intervals were classified within 30 minutes intervals, 9:20-9:50, 9:55-10:25, 10:30-11:00, 11:05-11:35, 11:40-12:10 and 12:15-1255 hours of operations. From each time intervals of the harvesting, the height of the cut above the ground was measured, recorded, and compared by using a measuring tape.

3.11.2.4. Area covered

The area covered with in harvesting system for each time intervals was measured and compared to determine the total area coverage during field test. The amount of the area from different time segment was measured and total summation was the total area covered during harvesting with the machine. The areas were measured by using measuring tape and pegs in the rows to determine the length and the width of the rows to get area covered by harvesting systems.

3.11.2.5. Effective working width of the machine

For determining average effective working width of the machine at field, three runs were taken randomly. The measurement of the cumulative width of cut for consecutively three test runs was measured with in rows selected at random during test.

3.11.2.6. Theoretical field capacity of the machine

Theoretical field capacity of machine is the rate of field coverage that was obtained considering the machine was performing its function at 100% of the time at the rated speed and always covered 100% of its rated width.

The theoretical field capacity was calculated as the following equation 3.64.

$$TFC = \frac{W\ x\ S}{10} \qquad 3.64.$$

Where: TFC = theoretical field capacity

W = rated width of machine, m

S = speed of the travel, m/s

3.11.2.7. Effective field capacity

The effective field capacity is the total area covered in an operation to the total time taken to complete operation. The machine was operated for continuous field work with a fixed time and the area covered during the period was measured to determine the average output per hour. The effective field capacity was calculated as equation 3.65.

$$\text{Effective field capacity (ha/h)} = \frac{\text{Area covered (ha)}}{\text{Total time taken to finish the area(h)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.65.$$

3.11.2.8. Field efficiency of the machine

According to the ASABE 2014 standard, the field efficiency of the machine is defined as the ratio of time the harvesters operate at its rated productive speed to the total field time (ASABE standard EP 496.3., 2014). During field tests, the productive and non-productive time was recorded per each time intervals to determine and obtain the amount of the time consumed in the field. The following table indicates the parameters used to record time with in each time intervals for productive and nonproductive activities. The overall summation of the time was total time consumed in the field during the performance test of the machine.

Table 3. 9. Time segment during field test

Time spent in different field activities(s)	
Productive time	T_1
Time for unclogging	T_2
Time for idle travel passes	T_3
Time for other nonproductive activities	T_4
Total time	$T_1+T_2 \ldots T_4$

The field efficiency was also calculated as the ratio of theoretical field capacity over actual field capacity to cover the area expressed in percentage.

$$\text{Field efficiency (\%)} = \frac{\text{Effective field capacity}}{\text{Theoretical field capacity}} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.66.$$

3.11.2.9. Harvesting cost of the machine

The cost required to finish the area was calculated. The cost was calculated from the standard of the factory paying system for 100 meters of the rows length. So to calculate the harvesting cost the rows areas was changed to hectares to determine Birr per hectares.

3.12. Ergonomic evaluation of the machine operators

Ergonomical evaluation is a tool to evaluate the energy expenditure of work, their physiological cost, and suitability of the method for farm workers and how long, they can work continuously without getting fatigued. This includes ambient conditions, tools, and materials, methods of work, and organization of work. The performance of harvester not only depends on the constructional features but also on the workers who operate them. The performance of man-implement systems may be poor if ergonomics aspects are not given attention (Kamlesh, 2017).

3.12.1. The heart rate of the machine operators

The average heart rate during the operation and working conditions of the harvesters were measured by using putting a hand on the pulse of the operator's hand by using a stopwatch (beats/min.).

3.12.2. The oxygen consumption rate of the machine operators

The pulse rate or oxygen consumption rate is a good index of physical as well as the physiological load on the operator. The pulse rate is affected due to the force required, working time, and operator posture. Increased pulse rate also signifies muscular fatigue of subjects (Kamlesh, 2017). The laborer was allowed to relax for 10 min before the commencement of operation. The operator performs different heart rate, and pulse rate during harvesting and operating of the machine for each harvesting systems. Within different time intervals, the pulse rate of the operators was recorded and measured by using an oximeter. The operators allowed inserting their finger to the device and then the device showed the pulse rate of the operators. In this determining the maximum efficiency of the operators and identifying the correct time intervals to operate the machine and the efficiency of the operators was identified.

The oxygen consumption rate (amount of oxygen consumed by the whole body per unit time) was computed from the heart rate values of the operator and is given by the following equation (Singh *et al*., 2008).

Oxygen consumption rate (l/min) = 0.0114 × HR -0.68…………………………………..3.67.

Where: HR is heart rate

The energy expenditure rate (EER) was determined by multiplying the OCR work with the calorific value of oxygen as 20.93 kJ/l (Nag and Dutt, 1980). The energy cost of the operators thus obtained was graded as per the tentative classification of strains in different types of jobs (Kamlesh, 2017). It was expressed as shown in Table 3.12.

Table 3. 10. A tentative classification of strains in a different type of works

Grading	Physiological response		
	Heart rate (bpm)	Oxygen uptake (l/min)	Energy expenditure (kcal/min)
Very light	<75	<0.35	<1.75
Light	75-100	0.35-0.70	1.75-3.5
Moderately heavy	100-125	0.70-1.05	3.5-5.25
Heavy	125-150	1.05-1.40	5.25-7.00
Very heavy	150-175	1.40-1.75	7.00-8.75
Extremely heavy	>175	>1.75	>8.75

3.12.3. Body mass index of the machine operator

Body mass index, also called BMI, is a calculation of a correlation between a person's height and weight that categorizes him or her as underweight, of normal weight, overweight or obese, assuming a normal body composition. Underweight is considered a BMI of 18.4 or lower. A BMI of normal weight is any number between 18.5 and 24.9. The overweight range is between 25 and 29.9, with anything above that being considered obese. Regardless of activity level, a minimum level of energy is required to sustain the body's everyday functions. Resting metabolism, the number of calories needed to supply the body with the minimum level of energy, differs between individuals depending on variables such as age, weight, body composition, and energy expenditure. Body mass index was calculated as the following formula expressed by the health education program for developing communities.

$$\mathrm{BMI} = \frac{\mathrm{Weight\ (kg)}}{[\mathrm{Height\ (m)}]^2} \quad \text{..}3.68.$$

3.13. Cost analysis

Estimation of hourly operational costs of the harvester machine was based on the capital cost of the harvester, interest on capital, cost of repairs and spare parts, labor cost, and depreciation (Kepner *et al.,* 2005 and Kamboj *et al*., 2012). The operational cost components of the prototype machine were estimated in Birr (ETB). The operational cost of the machine is calculated and determined in the appendices.

3.13.1. Fixed cost

The fixed cost was calculated by the following steps.

3.13.1.1. Depreciation

Depreciation is the reduction in the value of an asset due to usage, the passage of time, wear and tear, technological outdating or obsolescence, etc. According to (Kepner *et al.*, 2005), the annual depreciation was calculated as follows by equation 3.69.

$$D = \frac{C-S}{L \times H} \quad \text{..}3.69.$$

Where: D = Depreciation per hour (ETB/hrs.), C = Capital investment cost (ETB), S = Salvage value, 10%of the capital investment, ETB, L = Life of the machine in hours or years

3.13.1.2. Interest

Interest is calculated on the average investment of the machine taking into consideration the value of the machine in the first and last year. The annual interest on the investment can be calculated as equation 3.70 (Kepner *et al*., 2005).

$$I = \frac{C \text{ x } S}{2} \times \frac{i}{H} \quad \text{..}3.70.$$

Where: I = interest per hour, ETB/hr., i = Interest per hour (10 % per year, C = Capital investment cost (ETB), S = Salvage value, 10%of the capital investment, ETB

3.13.1.3. Housing, Taxes, Interest and Insurance

Each of the above titles was calculated as 1% of the initial cost of the machine.

Housing cost per hour (ETB/hr.) = 1% of the initial cost of the machine.....………..……3.71.

Taxes cost (ETB/hr.) = 1% of the initial cost of the machine…………………….….…….3.72.

Insurance cost (ETB/hr.) =1% of the initial cost of the machine…………………………….…….3.73.

Interest (ETB/hr.) = 1% of the initial cost of the machine………………..…….…….……3.74.

Total fixed cost (ETB/hr.) = Depreciation + Interest + Insurance + Taxes + House cost

3.13.2. Operating cost

The variable cost of the machine would be calculated by the following parameters.

3.13.2.1. Maintenance and repair cost

The repair and maintenance cost is a product of a machine's cost price and repair and maintenance percentage factor (Kepner *et al.,* 2005).

RM = 2.5 % × purchase price or capital investment per year…………………….………..3.75.

3.13.2.2. Fuel cost

Fuel cost was calculated as the amount of the fuel consumed in the field test.

3.13.2.3. Lubricant cost

It can be determined depending upon the maintenance cost or depending upon the oil price or oil consumption. The average lubrication cost is taken as 1.5% of fuel cost in ETB//hr. (Kamboj *et al.,* 2012).

3.13.2.4. Wages of the operators

Wages are calculated based on the actual wages of workers per hour. It differs from country to country.

3.13.3. The total cost of the operation per hour

The total cost per hour of the developed machine can be calculated by the summation of the fixed and variable cost per hour and calculated as equation 3.76.

Total operating cost per hour = fixed cost (ETB/hr.) + Variable cost (ETB/hr.) ……….…3.76.

3.14. Calculation parts

Table 3. 11. The overall calculated results were described below table

Parameters	Calculated results
Torque on the disc (equation 3.1.)	20.78 Nm
Optimum rpm to cut sugarcane (equation 3.2.)	1085 rpm
Power required cutting sugarcane (equation 3.3.)	$2.359\ \mathrm{kW} = 3.145\ \mathrm{hP} \approx 4.9\mathrm{hP}$

Angular momentum at the tip of the cutter (equation 3.4.)	23.49 $\mathrm{kgm^2/s}$
Centripetal force on the disc (equation 3.5.)	13,595.68 N
Torque on the engine shaft (equation 3.6)	10.7 Nm
Velocity of the belt (equation 3.7)	7.85 m/s
Rpm on the horizontal shaft (equation 3.8)	1085 rpm
Length of the belt (3.9)	1095.16 mm
Centrifugal tension of the belt (equation 10)	340.43 N
Output power on the horizontal shaft (equation 3.12)	1215 W
Power transmitted over the belt (equation 3.13)	33.05 %
Force required to drive the belt (equation 3.18)	154.76 N
Power transmitted per belt (equation 3.20)	1214.86 W
The number of belts required (equation 3.21)	1
The bending stress of the horizontal shaft (equation 3.22)	472,050.95N
The bending moment of the horizontal shaft (equation 3.23)	0.00578 Nm = 5.788 Nmm
Diameter of the horizontal shaft (equation 3.24)	22.62 ≈ 23 mm
Force distribution on the shaft	
Total weight on the shaft	185 N
W_A	66.27 kg m/s^2 = 66.27 N
W_B	118.73 kg m/s^2 = 118.73 N
Moment at point A (equation 3.25)	88 N
Moment B (equation 3.26)	97 N
Bevel gears design result and its specifications (table 3.6)	
velocity ratio or input gear ratio	1
Number of teeth	Z_1 = 17 and 17
Module (m)	3
Pitch diameter d_1 and d_2	51 and 51
Pitch cone angle for pinion and gear [degree]	45° and 45°
Outer cone distance (R_e) [mm]	36.06
Face width or tooth flank width, b [mm]	12.02
Mean cone distance (R_m) [mm]	30.05
Addendum (h_a) [mm]	3

Dedendum (h_f) [mm]	3.564 mm
Working depth (h_w) [mm]	6
Whole depth (h_l) [mm]	6.614
Clearance (c) [mm]	0.614
Dedendum angle (θ_f) [degree]	5.64°
Addendum angle (θ_a) [degree]	4.755°
Outer cone angle for pinion and gear (δa_1 and δa_2) [degree]	49.755° and 49.755°
Root cone angle for pinion and gear (δf_1 and δf_2) [degree]	39.36°and 39.36°
Outside diameter for pinion and gear (da_1 and da_2) [mm]	55.24 and 55.24
Weight calculation of the machine components	
Area of the frame (equation 3.29)	600 mm^2
Volume of the frame(equation 3.30)	0.00168 m^3
Mass of the frame(equation 3.31)	13.2 kg
Weight of the frame(equation 3.32)	129.49 N
Weight of the bottom cutter(equation 3.33)	37.47 N
Weight of the top cutter(equation 3.34)	16.65 N
Area of the bottom disc(equation 3.35)	70,650 mm^2
The volume of the disc(equation 3.36)	0.000423 m^3
The weight of the disc(equation 3.37)	32.56 N
The top disc area(equation 3.38)	70,650 mm^2
The volume of the top disc(equation 3.39)	0.000211 m^3
The Mass of the top disc(equation 3.40)	1.65 kg.
The weight of the top disc(equation 3.41)	16.18 N
Volume of the safety frame(equation 3.42)	0.001322m^3
The Mass of the safety frame(equation 3.43)	10.39 kg.
The weight of the safety frame (equation 3.44)	101.92 N
The mass of the motor cover(equation 3.45)	5.65 kg
The weight of the motor cover(equation 3.46)	55.42 N
The volume of the horizontal shaft(equation 3.47)	0.00215 m^3
The mass of the horizontal shaft(equation 3.48)	16.89 kg

The weight of the horizontal shaft(equation 3.49)	165.69 N
Area of the vertical shaft(equation 3.50)	0.0007065 m^2
The volume of the vertical shaft(equation 3.51)	0.00102 m^3
The mass of the vertical shaft(equation 3.52)	8.01 kg
The weight of the vertical shaft(equation 3.53)	78.57 N
The volume of the pulley (equation 3.54)	0.000538m^3
The mass of the pulley(equation 3.55)	4.22 kg
The weight of the pulley(equation 3.56)	41.39 N
The area of handle(equation 3.57)	0.000176 m^2
The volume of the handle(equation 3.59)	0.000316 m^3
The mass of the handle(equation 3.60)	2.48 kg
The weight of the handle(equation 3.61)	24.32 N
Force required to drive the harvester(equation 3.61)	97.62N
Torque on the ground wheel(equation 3.62)	29.28 Nm
Total weight	699.66 $\times$ 2% =713.35 N

3.15. Data analysis

The data obtained from field tests were analyzed by using software SPSS and represented with tables and graphs.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

The sugarcane harvesting machine was designed, developed, and fabricated. During field test the working principles of the designed and the developed machine was discussed, compared, and presented. As shown in the figure of appendix B different parameter was measured, and recorded in mechanical harvesting activities in the field. The results obtained during field tests were measured by using different equipment and materials as per measurement types and requirements and analyzed by using software SPSS.

4.1. Performance analysis harvesting system in the factory

The manual harvesting system was time-consuming, needs high laborer, operate with less quality, and high cost. It is not comfortable for laborers and leads to disease and injuries. The manual harvesting system causes spinal cord disease of operators due to striking with the sugarcane for more hours. The data collected from foreman and laborers of the factory indicates that more than 3 harvesters were damaged on average. The data obtained was by using structured questions for a foreman and laborers. From the total number of the respondents, each number of yes or no results was divided to the total number of the sample to determine the percentage. As a summary, the following table gives the overall percentage of weakness and strength of the manual harvesting system.

Table 4. 1. Weakness and strength of manual harvesting system

S. No	Parameters and Total number of respondents (10)	Number of responses	
		Yes (%)	No (%)
1.	Time and energy-consuming	100	0
2.	Injuries and pain	100	0
3.	Comfortable	10	90
4.	Expose for others disease	90	10
5.	Are you using PPE	20	80
6.	Hard to cut the cane stem	80	20
7.	Increase household income	60	40

4.2. Performance evaluation sugarcane harvester machine

The performance evaluation of the machine was conducted in the Wonji Shoa sugar factory farm field Dodota sub-branch. Both laboratory and field test was conducted for 4.9 hP diesel engine operated sugarcane harvesting machine.

4.2.1. Laboratory test

The visual observation was conducted during the laboratory test. The following parameters were tested.

- Before starting the machine, the machine part was checked carefully whether they are in the correct position or not
- As the machine running there was small and negligible vibration from the motor
- Observing rotating parts weather they running in appropriate conditions or not.
- Nut and bolts were checked and they tightened as good
- Moving the machine from one position to another position to check some disassembled parts
- Checking the machine rotating parts sound, noise and motor conditions
- The machine was easy to start, stop, and control.

Table 4. 2. Laboratory test of the machine

Parameters	Specifications
Input power	3.68 KW or 4.9 HP
Number of discs	Two discs
The dimension of the discs	Both discs have an equal diameter which was 300 mm.
Number of cutters	There are 10 cutting device which means 6 for bottom disc and 4 for top disc
Power transmission system	Belt pulley system
Weight of the machine	713.35 N

4.2.2. Data analysis of the field test

The measured data were analyzed to determine the machine harvesting field capacity, field efficiency, the physical structure of the sugarcane such as diameter of the cane, height of the sugarcane, height of the cut above the ground, other parameters like speed of the operators, area covered, cost of harvesting, row space, lodging of the sugarcane, and pulse rate of the operators with in different time intervals. The data obtained from the field test was analyzed by using SPSS software.

4.2.2.1. Diameter and height of the sugarcane

The average diameter at the bottom, middle and top was calculated from harvested field. The mean average diameter of the sugarcane obtained from the field test was obtained to be 26.79mm, 25.1mm, and 22.85 mm for bottom, middle and top of the sugarcane respectively. The average bottom diameter of the sugarcane was greater than the average top diameter by 14.7% and from average middle by the 6.3%. The analysis of variance (ANOVA) revealed that the sugarcane and the diameter condition was highly significant effect ($p < 0.05$) between rows.

Table 4. 3. One way ANOVA of the height for three rows

Components	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	149.0409	8	18.63011	8.575596	2.17205E-08
Within Groups	175.969	81	2.172457		
Total	325.0099	89			

4.2.2.2. Height of the sugarcane

The height of the sugarcane was one factor for the harvesting efficiency of the machine. From this height of the sugarcane in the harvested field about 35.67% of the height variation between longer and shorter sugarcane from the same field was recorded and determined. The analysis of variance (ANOVA) revealed that the sugarcane and the height condition had no significant effect ($p > 0.05$) between rows.

Table 4. 4. One way ANOVA of the height for three rows

Components	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	667.267	2	333.633	1.144	.333
Within Groups	7872.900	27	291.589		
Total	8540.167	29			

4.2.2.3. Height of the cut

The height of the cut above the ground was determined and compared between the rows. It depends on the row depth variation, amount of the water in the rows and conditions of the soil. From each rows about 3.4% height variation was observed between row_1, row_2 and row_3. About this percentage of the sugar content was left due to depth variation, soil condition and amount of the water in the rows. The analysis of variance (ANOVA) revealed that the harvesting machine conditions and the height of the cut above the ground had no significant effect ($p > 0.05$) between rows.

Table 4. 5. One way ANOVA of the height of the cut above the ground for three rows

Dependent	Source of the variance	Sum of Squares	df	Mean Square	F	Sig.
height	Between Groups	.160	2	.080	.576	.574
	Within Groups	2.085	15	.139		
	Total	2.245	17			

About 18.46% variation of the cut height was measured during field test between highest and lowest height of the cut above the ground. This amount of the juice content was left due to variation of the depth of the rows during harvesting by the harvesting the machine.

4.2.2.4. Area covered

The amount of the area covered in each time intervals was reducing and minimizing for harvesting systems as the working time increase and continuous. It was directly related with the speed of the operators, field conditions and population of the sugarcane in the between rows. The operators need for rest, pause of the work and fatigue was observed in the field test. The analysis of variance (ANOVA) revealed that the harvesting machine conditions and the height of the cut above the ground had no significant effect ($p > 0.05$) between rows. The maximum area coverage118.5 m^2 was obtained at drum speed of 1085 rpm.

Table 4. 6. One way ANOVA of the area coverage for three rows with in time intervals

Components	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.0034	2	.001	.547	.590
Within Groups	.00578	15	.0021		
Total	0.0092	17			

4.2.2.5. Speed of the operation

The other parameters were speed of the operators for harvesting the sugarcane with in different time intervals. Within increment of the time intervals the speed of the operators was also minimizing and reducing. The operator speeds reduce with in average of 10.23% per each time intervals. The analysis of variance (ANOVA) revealed that the harvesting machine speed and the operation within the rows had no significant effect ($p > 0.05$). The following table shows the relationship between the speeds of the machine in the rows.

Table 4. 7.One way ANOVA of the area coverage for three rows with in time intervals

Components	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.019	2	.00102	.323	.729
Within Groups	.046	15	.0015		
Total	.065	17			

4.2.2.6. Effective field capacity

The effective field capacity of the harvesting per hours was calculated and determined per each time intervals. The time intervals for harvesting systems were equal and but the area covered in harvested system was different due to speed of the operators in each time intervals. If the area coverage was small per time the effective field capacity was also minimizing and deceasing. The result obtained in the table below shows that the effective field capacities decrease with in average of 8% per each time intervals. The following tables indicate and shows that the effective field capacity for each time intervals for the mechanical harvested field.

Table 4. 8. Parameters for the effective field capacity

Time (minute)	Mechanical	
	Area (ha)	EFC (ha/hrs.)
30	2.4×10^{-3}	4.8×10^{-3}
60	2.2×10^{-3}	4.4×10^{-3}
90	2.05×10^{-3}	4.1×10^{-3}
120	1.82×10^{-3}	3.65×10^{-3}
150	1.6×10^{-3}	3.2×10^{-3}
180	1.4×10^{-3}	2.8×10^{-3}

The total effective field capacity which was covered during field test with mechanical harvesting systems was about 2.29 x 10^{-2} ha/hrs for within 1085 rpm for each time intervals which was 30 minutes intervals and the total field time was 180 minutes.

4.2.2.7. Field efficiency

The total time spent in the field test was recorded, compared and checked harvesting activities in the time intervals. For each productive pass, the total time for normal harvesting operation (productive time), and plugging removing, and another downtime (operator's time) was recorded (total nonproductive time). As the work continuous the down time of the operators was increasing and the area covered with in each time intervals was minimizing and decreasing. The additional factor was the speed of operators to push the machine in the row.

During field's tests, nonproductive time was greater and higher as compared with productive time. As the operators of the machine operate, the works for continuous time they need for rest and consumes more time to accomplish and cover the area. So long time operation of the workers were minimize the efficiency of the operators due to low speed operation and small area coverage.

From total time only 44.44% of the field test time was productive and other time was nonproductive in harvesting with machine. Next to this, the operators down time was second position during harvesting activities which indicates long time pause of work, chewing of the sugarcane and communication between others.

Table 4. 9. Summary of time segment for field efficiency test of two harvesting systems

Field activities	Mechanical harvesting	
	Times (second)	Percentage (%)
Productive time	4800	44.44
Nonproductive time		
Plugging cleaning	1890	17.5
Idle travel pass from one row to other	1200	11.12
Others (down time)	2910	26.94
Total time	10,800	100%

The following tables indicates that the field efficiency of the machine by using different parameter for calculations. The table indicates that the field efficiency of the field harvesting of the machine which was decreasing as the operation time increases. It was decrease with in average of 2.67 % for each time intervals.

Table 4. 10. Parameters for field efficiency test in mechanical harvesting activity

Time (hrs)	Speed (km/hrs.)	TFC (ha/hrs.)	EFC (ha/hrs.)	Efficiency (%)
0.5	0.028	0.00504	0.0048	95.23
1	0.0268	0.00483	0.0044	91.09
1.5	0.0258	0.00465	0.0041	88.17
2	0.023	0.00442	0.0036	81.44
2.5	0.0219	0.00395	0.0032	81.01
3	0.0195	0.00381	0.0028	79.7

4.2.2.8. Harvesting cost

The manual harvesting in the factory was different per age or year of sugarcane per cutting system in the field. For each year of sugarcane and cutting system, the payment per 100 meters was different and expressed as follows by the graph.

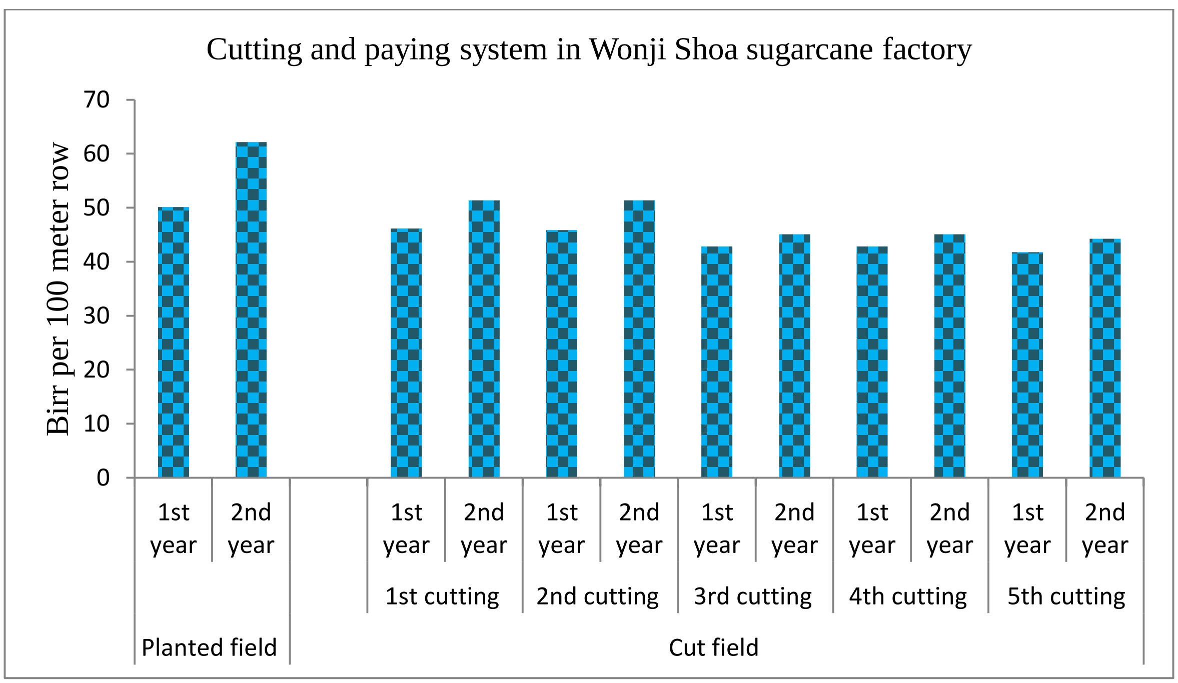

Figure 4. 1. Paying system in the Wonji Shoa sugar factory

The total area covered during field test was 118.5 m^2 for all time intervals. The cost required for harvesting this amount of the areas was directly related with the speed of the operators and harvesting activities. To cover 118.5 m^2 of the area of the mechanical harvested field, the amount cost was about 148.71 ETB.

4.2.2.9. Ergonomic parameters for the operator

The operator's conditions were measured, recorded, and checked for abilities to push the machine and harvesting with manual in the field. Physical fitness, average weight, average height, age, body mass index, heart rate, pulse rate, disabilities, breathing problem, and healthcare were measured and checked whether they were healthy or not. The measurement was conducted by using different materials and equipment as per the measurement. For each time interval, the operator condition was measured and noted for and every parameter listed above.

Table 4. 11. Physiological data of participants

Parameters	Checked results
	Operators 1 (machine operators)
Physical fitness	Good
Average weight (kg)	72
Average height (cm)	178
BMI	22.72
Age	31
Disability	No
Breathing conditions	Normal

4.2.2.10. Heart rate and pulse rate

As the working hours continuous the operator heart rate and pulse rate were increasing and continuous. The measurement was conducted seven times which was before starting work, 9:20-9:50, 9:55-10:25, 10:30-11:00, 11:05-11:35, 11:40-12:10, and 12:15-1255 hours of operations. As the pulse rate increase, the energy consumption was high and need high energy to perform the work (see Appendix A).

The result below table shows that the machine was classified as very light, light, moderately heavy, and heavy from (table 3.12.) tentative classifications of strains due to works. So, for the machine operator heart rate was increasing from the time interval of four and then classified as a heavy stage. At this level, the machine operator performs his work with less quality and under his efficiency.

Table 4. 12. Ergonomic aspect field observation data of sugarcane harvesters

Time	Mechanical harvester	
	Heart rate	Pulse rate
9:00 AM	68	94
9:20-90:50	98	96
9:55-10-25	110	98
10:30-11:00	117	98
11:05-11:35	121	98
11:40-12:10	126	97
12:15-12:55	126	98

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

A diesel engine driven sugarcane harvester has been designed and fabricated with locally available materials to match the need and alleviate the difficulties during harvesting the sugarcane by manually, and easily purchased by small and medium scale farmers. It is simple and does not require any special skill to operate. The performance testing and evaluation of the prototype of harvester machine was height of the cut above the ground, field capacity, field efficiency, area covered and harvesting cost. With proper attention to its maintenance which may include; regular lubrication of moving parts, replacement of worn-out/ damaged parts, cleaning and proper storage after use, this equipment will serve and adequately alleviate the sugar factories and farmers difficulties in sugarcane harvesting. Most importantly, the prototype harvester can be efficiently, effectively and economically used by the majority of Ethiopian sugar factories and small holder farmers which produce sugarcane.

5.2. Recommendations

The following suggestions were explored to improve the performance of five horse power diesel engine motor driven sugarcane harvester

- ✓ The manual harvesting of sugarcane was not efficient and confortable even for harvesters, so it was possible to use the developed machine by redesigning and developing if the developed machine was not suitable for operators in the different area due to operators types (sex type) and climatic conditions.
- ✓ The developed machine was only for sugarcane harvesting purposes, but it was possible to redesign for harvesting the maize and other related crops which was similar with that of sugarcane.
- ✓ The machine may be tested for similar crops which were only for sugarcane and the feedback received may be used for further design requirement of the height of the sugarcane which was automatic and adjustable type of the height controller.
- ✓ Consideration should be made to reduce the weight and cost of the planter.
- ✓ Promotion and dissemination of the technologies has to be done to end users.

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APPENDIX

Appendix A_1: Analysis of Variance and descriptive statistics for height of cut above the ground

Row 1		Row 2		Row 3	
Mean	5.883333	Mean	5.683333	Mean	5.683333
Median	5.9	Median	5.75	Median	5.6
Standard error	0.181506	Standard error	0.149257	Standard error	0.11949
Std. deviation	0.444597	Std. deviation	0.365605	Std. deviation	0.292689
Sample variance	0.197667	Sample variance	0.133667	Sample variance	0.085667
Range	1.2	Range	0.9	Range	0.8
Sum	35.3	Sum	34.1	Sum	34.1
Maximum	6.5	Maximum	6.1	Maximum	6.2
Minimum	5.3	Minimum	5.2	Minimum	5.4

Appendix A_2: Analysis of Variance and descriptive statistics for height of the sugarcane

Row 1		Row 2		Row 3	
Mean	165.4	Mean	170.2	Mean	176.9
Median	160.5	Median	173.5	Median	179
Standard error	6.96212	Standard error	4.28382	Standard error	4.544716
Std. deviation	22.01616	Std. deviation	13.54663	Std. deviation	14.37165
Sample variance	484.7111	Sample variance	183.5111	Sample variance	206.5444
Range	71	Range	44	Range	37
Sum	1654	Sum	1702	Sum	1769
Maximum	199	Maximum	191	Maximum	194
Minimum	128	Minimum	147	Minimum	157

Appendix B: Pulse rate measurement

Pulse rate measuring devices is used to measure the operators pulse rate by inserting the finger in to the device. It shows the pulse rate of the operators in each time intervals of the operators.

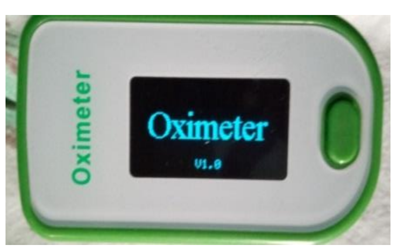

Figure: Oximeter for pulse rate measurement for machine operators

Photography of the sugarcane harvester machine field test



Appendix C: Production and operational cost

Table C_1: Materials for construction of harvesting machine and cost

No.	Materials list	Standard size	Total quantity	Rate	Total price
1	5 HP diesel engine motor		1	10,000	10,000
2	Mild steel 3mm thick	3 x 2 x 300 mm	600 mm^2	120	550.00
3	Mild steel 6 mm thick	6 x 2 x 300 mm	600 mm^2	120	550.00
4	Stainless steel 3 mm	3 x 210 x 150 mm	31,500 mm^2	300	600.00
5	Flat sheet metal 6mm thick	6 x 800 x 600 mm	480,000mm^2	1000	480.00
6	Mild steel round	Ø50 mm x 1100 mm	1	600	600.00
		Ø30 mm x 1200 mm	1	450	450.00
7	Cast iron	Ø138 mm	1	400	400.00
		Ø50 mm	1	250	250.00
8	Round bar	Ø30 mm x 590 mm	590 mm	500	500
9	Flat sheet metal 4 mm	4 x 1000 x 200	1200000 mm^2	1200	720.00

	thick	mm			
10	V-belt	B-49	1095.15 mm	500	500.00
11	Bearings (Pcs)	6202/16 mm	7 Pcs	250	1750.00
12	Metal bolt and nut	M-12 x100	8 Pcs	30	240.00
13	Metal bolt and nut	M-20 x 120	4 Pcs	45	180.00
14	Electrodes	Ø2.5	3 package	250	900.00
14	Paint		1 liter	150	150.00
				Subtotal	**18,820**

Table C$_2$: Machine and labor cost for construction of the machine

No.	Type of machine	Machine cost/hrs.	Working hours	Total cost	Labor cost/hrs.	Labor price/hrs.	Total cost
1	Lathe machine	150	4:30	645	6.25	40:30	251.875
2	Grinding machine	20	2:30	46	6.25	20:30	126.875
3	Universal metal cutting	11	2:00	22	6.25	20:00	125
4	Welding machine	60	4:00	240	6.25	40:00	250
5	Rolling machine	30	1:30	39	6.25	10:30	64.375
6	Bending machine	30.5	1:30	39.65	6.25	10:30	64.375
7	Power hack saw	40	2:00	80	6.25	20:00	125
8	Drilling machine	30	1:30	39	6.25	10:00	62.5
			Subtotal	1150.65		Subtotal	1070
						Total machine and labor cost	2220.65 ETB

Table C$_3$: Cost summary

No.	Cost variables	Cost
A	Raw materials cost	18,820
B	Material wastages (2.5%)	458
C	Machine cost	1150.65
D	Labor cost	1070

E	Overhead cost 5% (C+D)	111.0325
F	Profit 10% (A+B+C+D+E)	2160.96
G	Selling tax 15% (A+B+C+D+E+F)	3565.59
	Selling price	27,336.23

Table C_4: Cost of operation per hour for harvester machine

Cost of the machine (C)	27,336.23
Assumptions	
Life of the machine (L), years	10
Annual working hours (H), hrs.	1500
Salvage value (S)	10% of capital cost
Interest rate (i)	10% per annum
Fuel cost	1 liter = 19 ETB for testing the machine
Wage per day of 8 hrs.	100 ETB
A. Fixed cost	
Depreciation (D)	$D=\frac{C-S}{LxH} = \frac{27{,}336.73-2733.67\ ETB}{10\ year\ x\ 1500hr/year} = 16.04$
Interest (I)	$I = \frac{C+S}{2} \text{ x } \frac{i}{H} = \frac{27{,}336.73+2733.67}{2} \text{ x } \frac{\frac{0.1}{year}}{1000\frac{hrs}{years}}$
	= 1.5 ETB/hrs.
Tax and insurance cost	TI = 1% of the initial cost of the machine per year
	$TI = 0.01 \text{ x } 27{,}336.73 \text{ x } \frac{1\ year}{1000\ hrs}$ = 0.273 ETB/hrs.
Total fixed cost, ETB/hrs.	TFC= 16.04 ETB/hrs. + 1.5 ETB/hrs. + 0.273 ETB/hrs.
	= 17.813 ETB/hrs.
B. Variable cost	
Fuel cost (l/hrs.)	Fc = 1 liter per hour = 19 ETB/hrs.
Lubrication cost (LC)	LC = 1.5% x fuel cost = 0.285 ETB/hrs.
Repair and maintenance cost(RM)	RM = 2.5% of initial cost of machine
	=0.025 x 27336.73x0.001 = 0.683 ETB/hrs.
Wages for operators	6.25 ETB/hrs.
Total variable cost, ETB/hrs.	TVC= 19 ETB/hrs. + 0.285 ETB/hrs. +0.683 ETB/hrs.

	+ 6.25 ETB/hrs. = 26.218 ETB/hrs.
The total cost of the machine,	17.813 ETB/hrs. + 26.202 ETB/hrs.
ETB/hrs.	TC =44.03 ETB/hrs.

Therefore, the cost of the operation of the sugarcane harvesting machine was 44.03ETB/hrs.

Appendix D: Operation manual

As the operators ready to harvest, he or she start the diesel motor with starting cables. If the motor attained its optimum rpm then the operator can push it toward the sugarcane along the rows. During harvesting, he or she was follow the wheel of the machine was with in the furrow space and tries to adjust to cut all the cane from the top of the furrow. There was a front wheel that was ready to move any direction due to bearing activity and to minimize the load during changing direction and searching for cutting the cane. The harvested cane was dropped to the right side of the operator due to centripetal forces in which the bottom part of the sugarcane was attracted. After the operation, the operator can switch off the motor and stop operation and lastly clean and maintain for damaged parts.

Appendix E: Questionnaire for manual the harvesting in the field

Dear respondent, as part of my MSc study in Agricultural Machinery Engineering, I am undertaking a research study on the title, **"Design, development and performance evaluation of mechanical sugarcane harvesting machine."** The main purpose of this questionnaire is to collect data about the Wonji Shoa sugarcane harvesting system. The questionnaire would serve as a major input for research conducted in pursuit of academic purpose. Therefore, the respected respondents kindly requested to give your genuine response to the questions included here below in the structured questionnaire. I would like to make sure that the response of the respondents is confidential and secured. I would like to thank you in advance for your peacefulness and cooperation.

Please put a mark ***(√)*** on the box provided, if you have a comment please write up on the space provided.

Part I**. General Information.**

1. Name of the respondent………………………..2. Name of company………………………

3. Name of working department ………………….4. Working section/unit……………………

Part II**. Employee Characteristics**

1. Age of respondent ……………………..

2. Sex; Male ☐ Female ☐

3. How long have you been in the factory?

1-3 years ☐ 10-13 years ☐

4-6 years ☐ 13-16 years ☐

7-10 years ☐ 16 & above years ☐

Part III. Manual harvesting system (filled by Forman and Capo)

1. Are the laborers use PPE (personal protective equipment) during harvesting?

Yes ☐ No ☐

2. How many laborers were assigned in one row?

Only one ☐ Two ☐ Three ☐ Above four ☐

3. The time required finishing 100 meters of sugar

Two hours ☐ Three hours ☐ Four hours ☐ Five and above hours ☐

4. Employment type?

Contract ☐ Full time ☐

If yes, how many of them per day? ………………………………………………….

5. Level of education for laborers?

Class of 1-8 ☐ Class of 8-12 ☐ Diplomas ☐ Above degree ☐

Part III. Manual harvesting system (filled by Laborers)

1. Is the harvesting with manual time and energy-consuming?

   Yes ☐ No ☐

2. Do you have injured and pained during harvesting?

   Yes ☐ No ☐

3. Is the harvesting with the manual was comfortable as compared with other work?

   Yes☐ ☐

4. Are you using PPE?

   Yes ☐ No ☐

5. Is the payment per row fulfilling the income of your daily need?

   Yes ☐ No ☐