Mathematical Modeling of The Weight of Grain Straw during Conveying in Vertical Conveying Reaper Windrow

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Research article

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Abstracts

Analyzing the total weight of cut straws inside the conveyor is important in a vertical conveyor reapers machines to optimize the supply energy into the lugged belt conveyor system. This weight was mathematically modeled by considering the working mechanism of vertical conveyor reapers machines, corelating feeding rate of cut straws from cutter to conveyor and conveying rates of lugged belt conveyor. Then the mathematical model for total weight was defined by determining numbers of cut straws in front of each cutters or knives. The defined equation shows that the feed rate of cut straws into the conveyor is in arithmetic sequence fashion with equal initial value and common difference. The total weight of cut straws equation is an arithmetic series with positive common difference. The equation also shows that the numbers of cut straws in the conveyor increased in arithmetic progression when the numbers of cutters or knives increased. In general, the weight of cut straws in conveyor depends on mass of straw, gravitational acceleration, numbers of cutters or knives, forward speed of reaper, spacing of lugs, angular speed of conveyor pulley, diameter of conveyor pulley and diameter of straw.

Keywords: Grain Weight; Vertical Conveying Reaper; Reaper Conveyor; Feed Rate; Conveying Rate

1. Introduction

Vertical conveyor reapers are machines which are used to harvest grain crops such as wheat, barley, rice, soybean, and other cereal and oilseed crops. There are four types of Vertical conveyor reaper machines. These are self-propelled vertical conveyor reaper, tractor mounted vertical conveyor reaper, self-propelled riding type vertical conveyor reaper and self-propelled reaper binder (Department of Agriculture & Corporation of Mechanization and Technology, n.d.).

self-propelled vertical conveyor reaper machines cut the crops and conveys it vertically to one end and windrows the crops on the ground uniformly using lugged canvas conveyor belts. Tractor mounted vertical conveyor reaper cut the crop and held it in a vertical position and delivered to one side of the machine by lugged belt conveyors and fall on the ground in the form of a windrow perpendicular to the direction of movement of machine. Self-propelled riding type vertical conveyor reaper is a self-propelled unit in which the operator rides on the machine. Self-propelled reaper binder cut and convey vertically to the binding mechanism where it is tied by the twine and released to the ground in the form of bundles (Department of Agriculture & Corporation of Mechanization and Technology, n.d.)**.**

The weight of a cut grain straw is the sum of the weight of its shoot and spike. The weight of the shoot and spike of a grain depends on types of grain, genetic variety within a grain and environmental constraints. The weight of the shoot has a direct relation with its stem length. **Mekonnon (2014)** experimental proofed that the weight of barley spikes has direct relation with its spike length and numbers of grains per spike for different genotype barley. **Cui et al. (2011)** used to evaluate possible genetic relationships between plant height (PH) and plant height components (PHC) using conditional quantitative trait locus (QTL) mapping method. This study shows that plant height depends on genetic basis in wheat.

Shah et al. (2011) conducted a field experiment to assess the effect of tillage, mulch and time of N application on yield of wheat. This experiment shows that higher plant height was observed in surface seeded, mulched and half N at sprouting and half at CRI plot. And also grain yield (3.62 t ha^{-1}) and harvest index (39.35%) were significantly higher in surface seeded plot than conventionally tilled plot due to the higher number of effective tillers m^{-2}, longer spike length and higher spike weight, grain weight spike-1 and test weight. Similarly, mulched crop had also shown significantly higher grain and straw yield than non-mulched crop due to the longer spike length and higher grain weight $spike^{-1}$ and test weight**Error! Reference source not found.**. This research proof that the weight of wheat depends on environmental traits.

Wei et al. (2010) conduct a research to control the influence of the three most important agronomic traits of rice (Oryza sativa), yield, plant height, and flowering time by quantitative trait loci (QTLs) mapping. In this study, a newly identified QTL mapping, DTH8 (QTL for days to heading on chromosome 8), regulate plant height and its yield potential. This study shows that rice height depends on genetic basis.

Yan et al. (2011) report the cloning and characterization of Ghd8, a major QTL with pleiotropic effects on grain yield, heading date, and plant height. Based on this Ghd8 fine mapping greatly contributed to rice heading, plant height, and yield-related traits**Error! Reference source not found.**.

In general, all the Vertical conveyor reaper machines are driven by using different sources of input power. The input power is divided into cutter and conveyor sub systems. The conveyor power depends on the weight of crops conveyed at a time. One of the basic problems in vertical conveyor reaper machines is determining weight of straws to optimize amount of energy needed during conveying straws. The weight of grain straws depends on types of plant, genetic varieties and environmental constraint. The purpose of this study is to develop a mathematical equation which can be applicable to estimate the weight of grain straws during conveying for any types of crops harvested by vertical conveying reaper windrow.

2. Methods

- **Feed Rate Estimation**: defining mathematically the feed rate of cut straws into the conveyor using forward speed of machine and diameter of grain straw by studying the feeding mechanism into the cutter, cutting and controlling mechanism of the cutter of the Vertical conveyor reaper machines.
- **Conveying Rate Estimation**: defining mathematically the conveying rate of cut straw within the conveyor using speed of conveying belt and pitch of lug by studying the flat belt and lug geometry sequence, and star wheel geometry and sequence of the Vertical conveyor reaper machines.
- **Finding Numbers of Straws between the First Two Consecutive Lugs**: defining mathematically the cut straw conveyed between consecutive lugs. The distribution of numbers of straws examined and analyzed by using feed and conveying rates to get the numbers of straw between two consecutive lugs.
- **Finding total numbers of Straws Conveyed at a Time**: the total numbers of straws conveyed at a time determined by studying the sequence of the straws in front of each cutter or blade.
- **Determining total Weight of Straws**: defining mathematically the weight of the whole straw conveyed at a time by determining the initial value and common difference, and considering mass of grain and gravitational acceleration.

3. Results

3.1. Working Principle of Cutter System in Reapers

Tefera & Aschenaki (2019) designed and made a prototype of Multi-Crop Solar Powered vertical conveying reaper machine. A DC motor drives this reaper machine. The power is supplied into the DC Motor either from DC batteries or direct solar panels. As the DC motor starts, the power is transmitted to intermediate shaft through the belt pulley mechanism see **Figure 1**. This power is again transmitted to the camshaft through bevel gear assembly. When camshaft rotates, the positive return follower reciprocates back and forth using eccentric cam see **Figure** 2. At the same time, the cutter bar reciprocates back and forth together with follower since the attachment is rigid. When the cutter bar reciprocates, it cuts the grain. At the same time, the camshaft drives the lugged belt conveyor system through the pulley in order to collect the grains to one side.

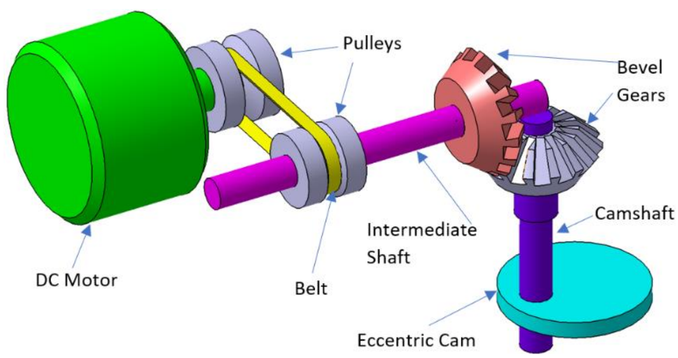

Figure 1 Power Transmission System (Tefera & Aschenaki, 2019)***Error! Reference source not found.***

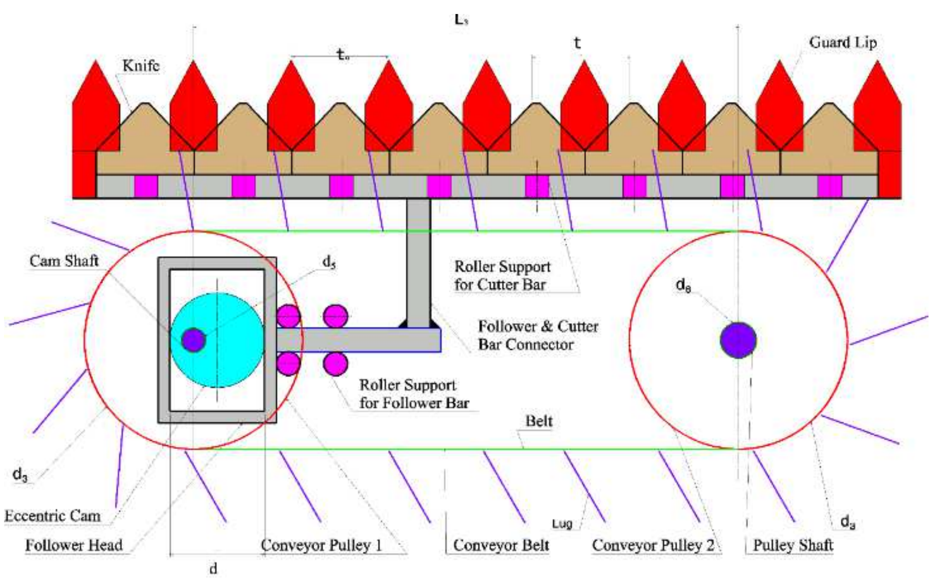

Figure 2 Basic Structure of Cutting and Conveying Mechanism (Tefera & Aschenaki, 2019)

3.2.Working Principle of Lugged Belt Conveyors

Figure 3 shows the schematic diagram of lugged belt conveyor and star wheel combination. In this diagram, the rotation of the camshaft is clockwise. The camshaft drives the conveyor pulley 1 in the clockwise direction. The conveyor pulley drives the lug and conveyor belt assembly in the clockwise direction. The lugged belt conveyor conveys the cut straws to the right together with the star wheel.

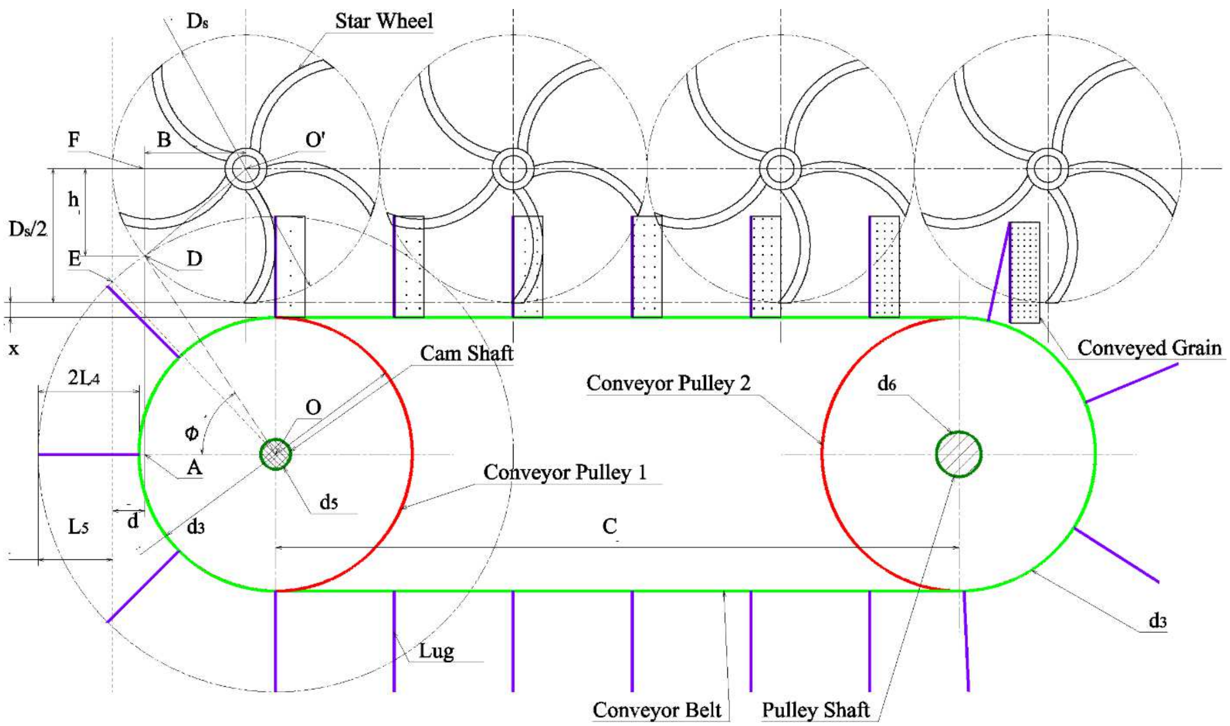

Figure 3 Schematic Diagram of Conveyor and Star Wheel System

3.3.Mathematical Modeling of Weight of Grain

The following assumptions should be bear in mind before developing the mathematical modeling of weight of grain.

Assumption 1: the distribution of crop plants is uniform throughout the field with optimum plant density of crops.

Assumption 2: the star wheels perfectly control the crops feed into the cutters i.e., the star wheel forces the feed crop into the cutters in rows and these rows of straws are close to each other about their diameter.

Assumption 3: All lugs are identical and installed at same spacing and angle on the flat belt see **Figure** 4.

Assumption 4: All cutters are identical and installed at same spacing see **Figure** 2.

Assumption 5: Each cutter gets inline rows of crop straws equally because the cutters are installed fixedly on a single straight cutter bar see **Figure** 2.

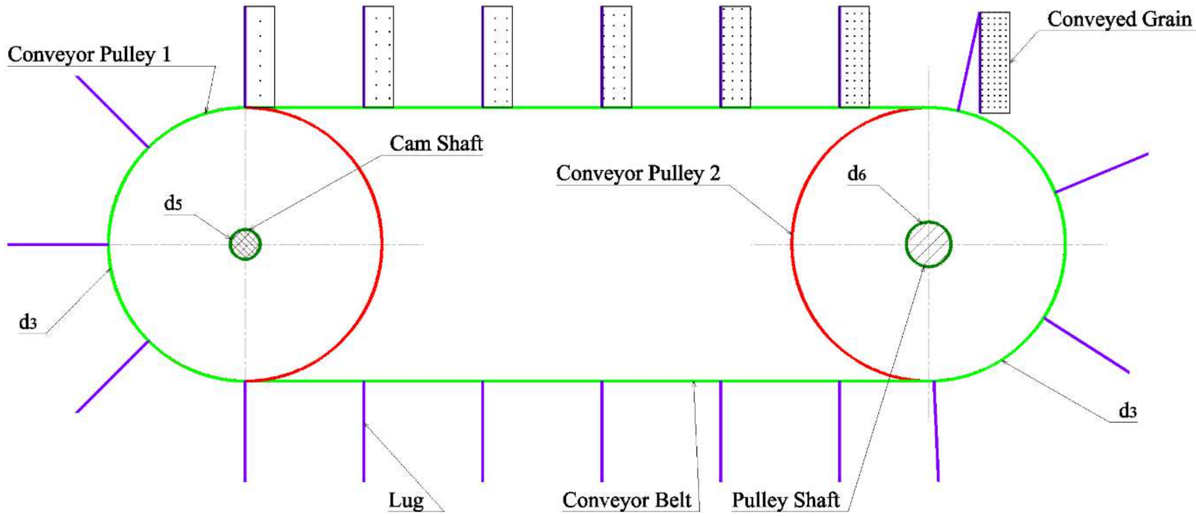

Figure 4 2D Representation of Conveyor System

The magnitude of conveying force F_c applied by the lugs depends on the weight of straw, frictional force between the straw and cutter bar surface, forward speed of the harvester, speed of the lug, pitch of lug and diameter of straw. The kinematics relations of straw and lug shall be first defined in order to get the conveying force F_c applied by the lugs. The kinematic analysis can be carried by considering the above four assumptions. Hence, the time t_s required to feed one straw into the knife is the ratio of diameter of straw (d_s) and forward speed of the harvester V_m.

$t_s = \frac{d_s}{V_m}$ -- *1*

The cut straw feed into the conveyor by the star wheel in each moment of cutting. The time taken to feed the cut straw to the conveyor must be less than or equal to cutting time of the knife or cutter t_s otherwise it will fall down. Therefore, the feed rate or frequency of cut straw feed into the lug becomes the ratio of each straw and time taken t_s during cutting. **Equation** $feed\ rate = \frac{1\ straw}{t_s} = \frac{V_m}{d_s}$ -- ------------------------------ 2 shows the numbers of straws feed into the conveyor in unit of time.

$$feed\ rate = \frac{1\ straw}{t_s} = \frac{V_m}{d_s} \text{ ------ } 2$$

The lug is under linear motion in the conveying side of the belt. The time (t_p) required for the lug to cover its pitch defined by using speed of belt (V_b) and pitch of lug (p). The speed of the belt is same as the tangential speed of (V_b) the conveyor pulley which is the product of angular speed (ω_3) of pulley and its radius ($\frac{d_3}{2}$).

$$t_p = \frac{p}{V_b} = \frac{2p}{\omega_3 d_3} \text{ ------ } 3$$

The conveying rate of the lug is the frequency of lug per unit time i.e., the ratio of one cycle of the lug to its pitch and time required for the lug to cover the pitch.

$$conveying\ rate = \frac{1\ cycle\ of\ lug}{t_p} = \frac{V_b}{p} = \frac{\omega_3 d_3}{2p} \text{ ------ } 4$$

The numbers of straws (n_1) feed into the first lug from the first cutter depends on the feeding and conveying rates. It has direct relation with feeding rate whereas inverse relation with conveying rate. This implies that the numbers of straws become higher when the feeding rate is high on contrary its numbers becomes few when the conveying rate too low. Therefore, the numbers of straws (n_1) feed into the first lug from the first cutter becomes the ratio of feeding and conveying rates.

$$n_1 = \frac{feeding\ rate}{conveying\ rate} = \frac{2V_m p}{\omega_3 d_3 d_s} \text{ ------ } 5$$

Equation $n_1 = \frac{feeding\ rate}{conveying\ rate} = \frac{2V_m p}{\omega_3 d_3 d_s}$ --

---------- 5 shows the numbers of straws conveyed in front of each cutters. The feed rate of straws is constant from all the cutters. However, the numbers of straws are not equal in front of all the lugs which are under conveying the cut straws. Because the conveyor moves all the cut straws to one side. There is common difference (d) of straws between consecutive lugs. This implies that the distribution of grain is in arithmetic sequences. The numbers of cut straws conveyed between consecutive lugs can be defined by using the general formula of arithmetic sequences (mathplanet, n.d.). All the cutters feed same numbers of straws into the conveyor. Hence, the first term n_1 and common difference d becomes same ($n_1 = d$). The numbers of straws n_i conveyed in front of the i^{th} cutter or knife defined using the general formula of the arithmetic sequences as follows.

$n_i = n_1 + (i-1)d = n_1 + (i-1)n_1 = in_1 = i\frac{2V_m p}{\omega_3 d_3 d_s}$--- 6

Where i-is the total numbers of cutter or knife installed on the cutter bar

Therefore, the total numbers of straws n_s conveyed through the lugs becomes the sum of the arithmetic sequence defined in **equation** $n_i = n_1 + (i-1)d = n_1 + (i-1)n_1 = in_1 = i\frac{2V_m p}{\omega_3 d_3 d_s}$-- ------------------- 6 using the general formula of arithmetic series (mathplanet, n.d.).

$n_s = \frac{i}{2}(n_1 + n_i) = \frac{i}{2}(n_1 + in_1) = \frac{i}{2}(i+1)n_1 = (i^2 + i)\frac{V_m p}{\omega_3 d_3 d_s}$-- 7

The total weight of the straws W_{sT} conveyed at a time becomes the product of weight of a straw W_s and total numbers of straws n_s.

$W_{sT} = W_s n_s = m_s g n_s = m_s g(i^2 + i)\frac{V_m p}{\omega_3 d_3 d_s}$ -- 8

Where m_s-mass of any type of crop straw and g- gravitational acceleration.

4. Discussion

There are eight parameters which have contribution on the total weight of straw conveyed at a time under full operation as shown in **equation Error! Reference source not found.**. Among these, five parameters have direct relation with total weight of straws i.e., mass of straw m_s, gravitational acceleration g, numbers of cutters or knives i, forward speed of reaper V_m, and spacing of lugs p. Whereas three parameters have inverse relation with total weight of straws i.e., angular speed of conveyor pulley ω_3, diameter of conveyor pulley d_3 and diameter of straw d_s.

- **Mass of straw m_s**: The weight of straws depends directly on the mass of crop species (rice, wheat, barley, Teff, etc.). The mass of crop species depends on the masses of its height of shoot and spike. The heavier the masses of straws species, the heavier the total weight of conveyed straws.
- **Numbers of cutters or knives i**: The numbers of straws conveyed at a time becomes increased when the numbers of cutters or knives i are increased because the cutters or knives cut more crops and feed into the conveyor. This increases the weight of straws in the conveyor. In same manner, the numbers of straws conveyed at a time becomes decreased when the numbers of cutters or knives i are decreased because the

cutters or knives cut few crops and feed into the conveyor. This decreases the weight of straws in the conveyor.

- **Forward speed of reaper $\boldsymbol{V_m}$**: The feed rate of uncut straw depends on the forward speed of the reaper. So that the weight of cut straws depends on the fastness or slowness of the harvesting machine. When the forward speed of the reaper is fast, the weight of the cut straws becomes heavy in the conveyor by keeping other parameters constant.
- **Spacing (Pitch) of lugs p**: the spacing or pitch between two successive lugs also has direct relation with weight of the cut straws in the conveyor. When the spacing/pitch is too far, it takes much time to reach on the cut straws for the lug. Hence, too many cut straws will be collected in front of the cutter or knife waiting for the lug to be conveyed.
- **Angular speed of conveyor pulley $\boldsymbol{\omega_3}$**: The angular speed of the conveyor pulley has inverse relation with the weight of cut straws inside the conveyor. Because when the angular speed of the conveyor is too fast, it conveys the cut straws in each moment of cutting. Hence, the numbers of straws collected in the conveyor becomes few. So that the weight of cut straws becomes light in the conveyor.
- **Diameter of conveyor pulley $\boldsymbol{d_3}$**: the effect of the diameter of conveyor pulley similar with angular speed of the conveyor pulley because both increases or decreases the speed of the conveyor in the same fashion. Hence, the weight of straws becomes light in the conveyor when the diameter of conveyor pulley is large and the reverse is true.
- **Diameter of straw $\boldsymbol{d_s}$**: the last parameter (diameter of straw) has inverse relation with weight of cut straws in the conveyor. When the diameter is too large, it takes more to complete cutting of a single straw due to this reason the weight of cut straws becomes light.

In general. **equation** $W_{sT} = W_s n_s = m_s g n_s = m_s g(i^2 + i)\frac{V_m p}{\omega_3 d_3 d_s}$ -- 8 helps manufacturers and researchers that are working in the vertical conveying reaper windrow to optimize the energy requirement to convey cut straws. The total numbers of cut straws conveyed at a time is defined by an arithmetic series see **equation** $n_s = \frac{i}{2}(n_1 + n_i) = \frac{i}{2}(n_1 + in_1) = \frac{i}{2}(i+1)n_1 =$

$(i^2 + i)\frac{V_m p}{\omega_3 d_3 d_s}$--- 7 which is the sum of arithmetic sequences of **equation** $n_i = n_1 + (i-1)d = n_1 + (i-1)n_1 = in_1 = i\frac{2V_m p}{\omega_3 d_3 d_s}$-- 6. The arithmetic sequence in **equation** $n_i = n_1 + (i-1)d = n_1 + (i-1)n_1 = in_1 = i\frac{2V_m p}{\omega_3 d_3 d_s}$-- 6 has a positive common difference (d=n1) which indicated that the numbers of straws becomes increased when the numbers of cutters or knives are increased. It is obvious that the total weight of cut straws inside the conveyor has direct relation with total numbers straws see **equations** $n_s = \frac{i}{2}(n_1 + n_i) = \frac{i}{2}(n_1 + in_1) = \frac{i}{2}(i+1)n_1 = (i^2 + i)\frac{V_m p}{\omega_3 d_3 d_s}$--- 7 and $W_{sT} = W_s n_s = m_s g n_s = m_s g(i^2 + i)\frac{V_m p}{\omega_3 d_3 d_s}$ -- 8.

List of abbreviations

d-common difference

d_s-diameter of straw

d_3-pulley diameter

F_c-conveying force

g- gravitational acceleration.

i-total numbers of cutter or knife installed on the cutter bar

m_s-mass of any type of crop straw

n.d.-not defined

n_s-total numbers of straws

n_1-numbers of straws

p-pitch of lug

t_p- time required for the lug to cover its pitch

t_s - time required to feed one straw into the knife or cutting time of the knife or cutter

V_b-speed of belt

V_m-forward speed of the harvester

W_{sT}-total weight of the straws

ω_3-angular speed of pulley

Declarations

Availability of data and materials
Not applicable

Competing interests

The authors declare that they have no competing interests.

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Adama Science and Technology University support this research financially to make the prototype of Multi-Crop Solar Powered Vertical Conveying Reaper Windrow

Authors' contributions
Mr. Getaw has done all the activities in this manuscript.

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Figures

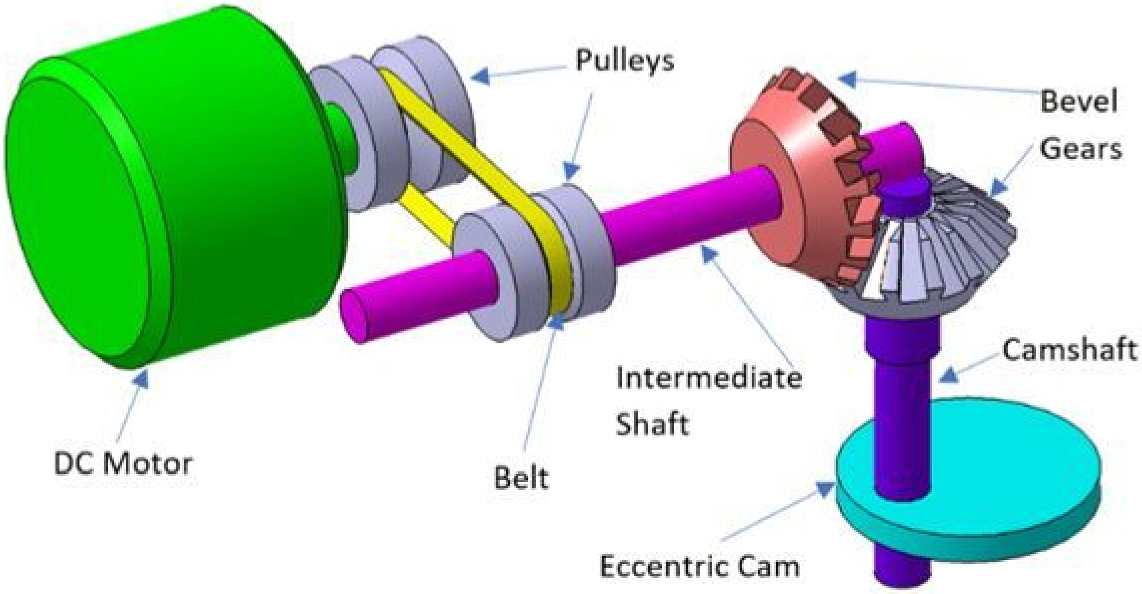

Figure 1

Power Transmission System (Tefera & Aschenaki, 2019)Error! Reference source not found.

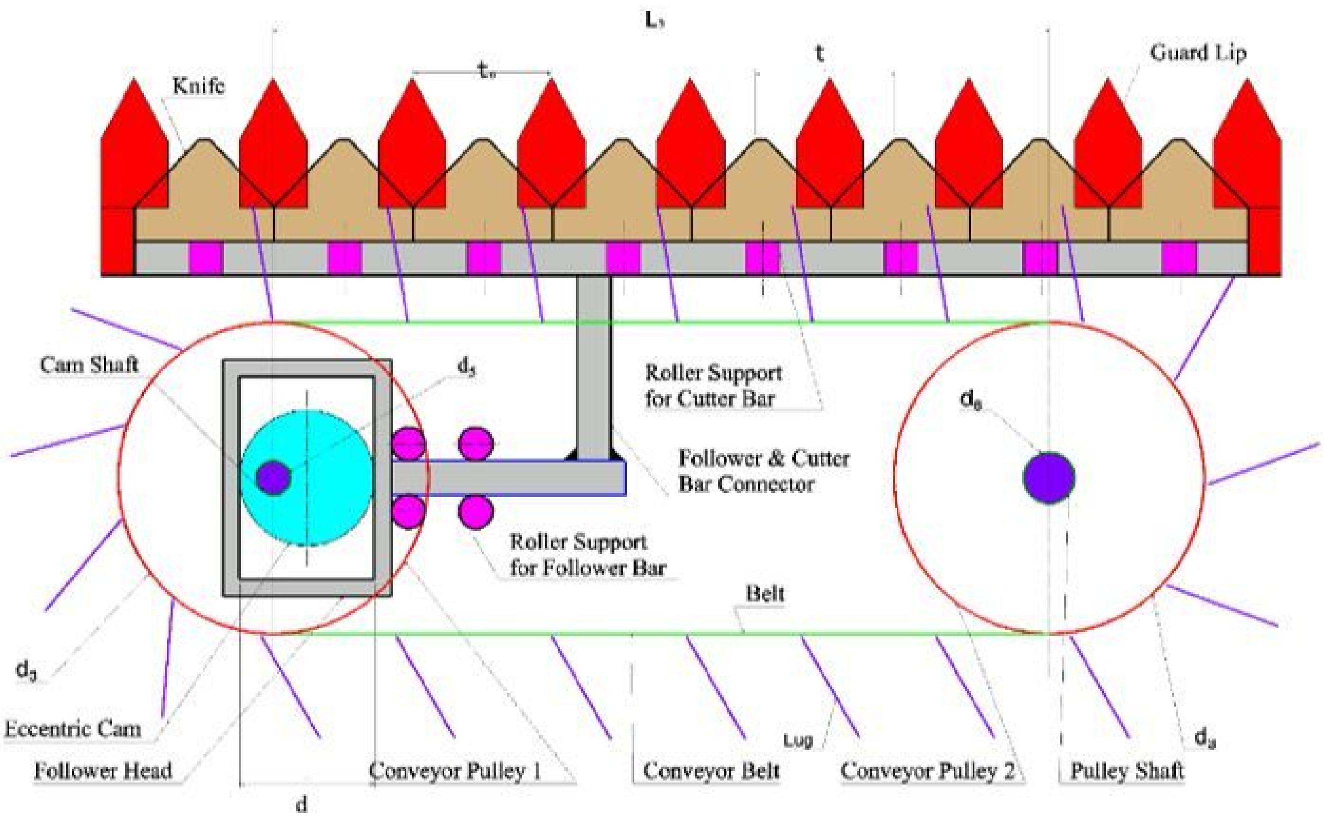

Figure 2

Basic Structure of Cutting and Conveying Mechanism (Tefera & Aschenaki, 2019)

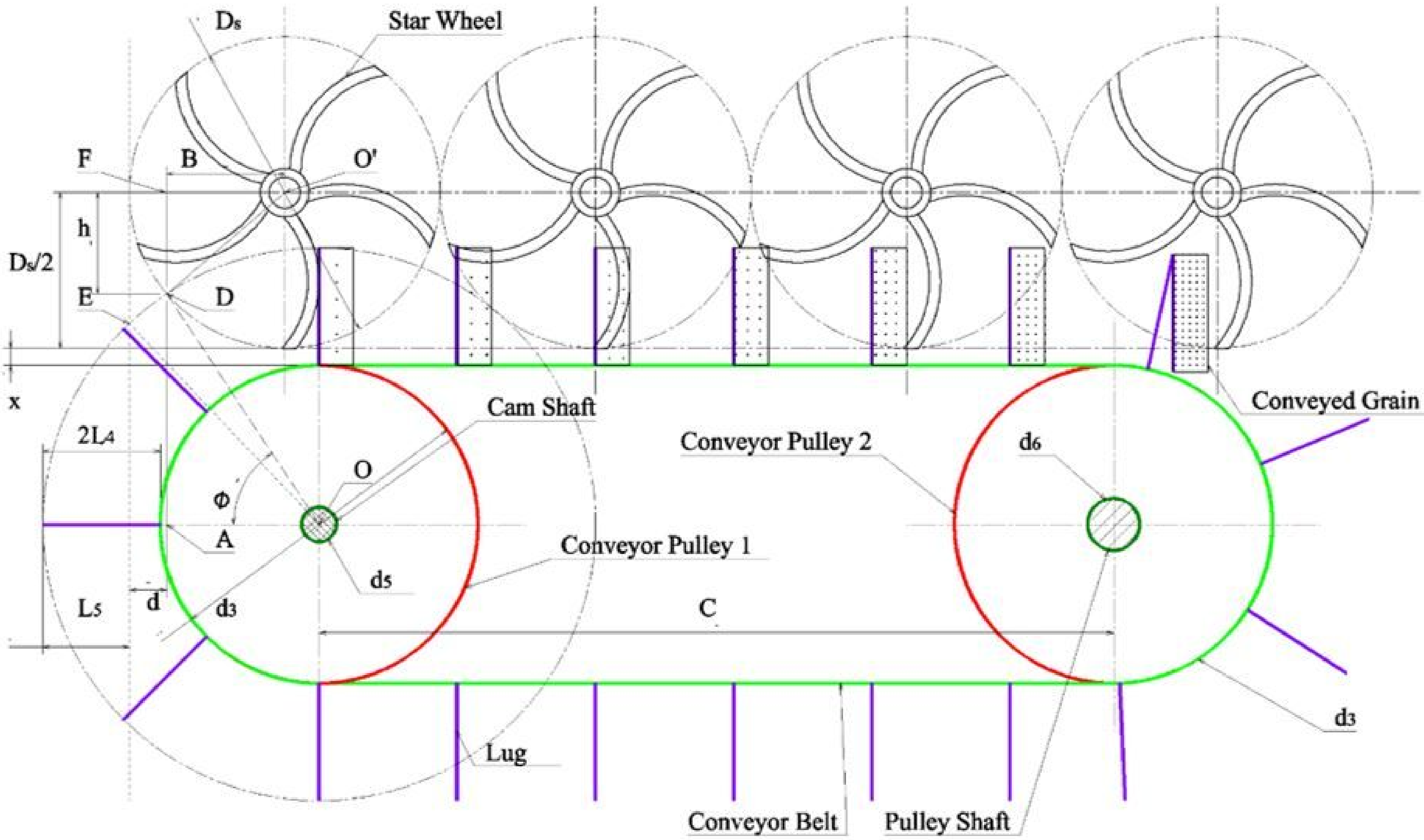

Figure 3

Schematic Diagram of Conveyor and Star Wheel System

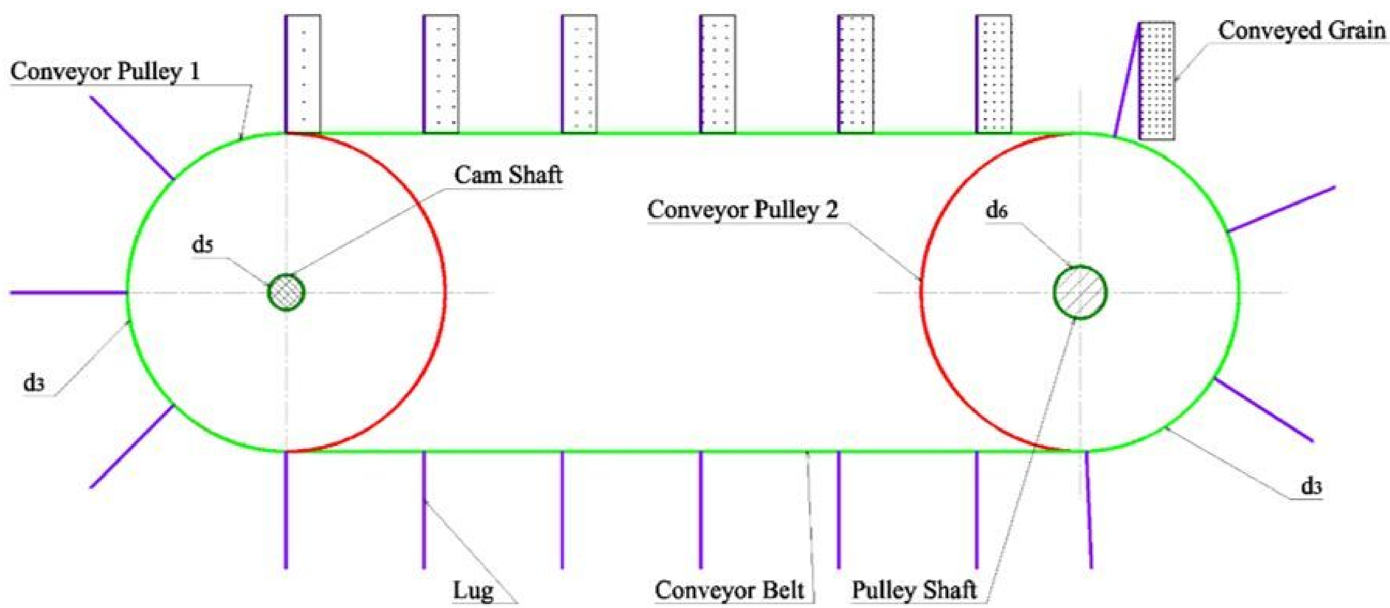

Figure 4

2D Representation of Conveyor System