OPTIMIZATION OF DESIGN PARAMETERS AND PERFORMANCE OF A PORTABLE COMMON BEANS (*PHASEOLUS VULGARIS L*) THRESHER

PATRICK WAFULA WAMALWA

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Optimization of Design Parameters and Performance of a Portable Common Beans (*Phaseolus Vulgaris L*) Thresher

Patrick Wafula Wamalwa

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

Signature: ………………………………………. Date: …………………………...

Patrick Wafula Wamalwa

This thesis has been submitted for examination with our approval as university supervisors.

Signature: ………………………………………. Date: …………………………...

Prof. Christopher L. Kanali, PhD

JKUAT, Kenya

Signature: ……………………………………… Date: …………………………...

Dr. Erick K. Ronoh, PhD

JKUAT, Kenya

Signature: ……………………………………… Date: …………………………...

Dr. (Eng.) Gareth M. Kituu, PhD

JKUAT, Kenya

DEDICATION

This thesis is dedicated to my wife Yvonne Mambiri Wamalwa, who has been a source of encouragement and inspiration during challenging times of my studies. I appreciate her prayers, understanding and support. To my parents Mr Festus Matiba Wamalwa and Mrs Beatrice Akatsa Wamalwa who have supported me throughout my life; when challenged in various levels of my education, they have prayed for God’s blessings on my endeavours. They have always cared and nurtured good character and positive attitude in me. In addition, they have immensely sacrificed in numerous ways to ensure that I pursue education to greater altitude of success.

To my brothers; Robert Wamalwa, William Wabwire and Gilbert Simiyu: for continuous support during my education. I also dedicate this thesis to my numerous friends, classmates and church members who gave me support throughout the process. I appreciate all what they have done, especially their prayers and advice when required in overcoming challenges encountered along my studies.

In a special way, this thesis is also dedicated to all my trainers of good will; the primary and secondary school teachers, University lecturers and all those who have immensely contributed to my success in academia. Finally, I dedicate this work to all who depend on traditional methods of common beans threshing that are manual, tedious, time consuming and have high mechanical breakages resulting to high losses.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANNs	Artificial Neural Network
AfDB	African Development Bank
BCR	Benefit Cost Ratio
EAT	East Africa Time
CIAT	The International Centre for Tropical Agriculture
FAO	Food and Agriculture Organization
JICA	Japan International Cooperation Agency
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KALRO	Kenya Agricultural and Livestock Research Organisation
MoEST	Ministry of Education, Science and Technology in Kenya
PV	Photovoltaic
RSM	Response Surface Methodology
RPM	Revolution Per Minute
SOBEE	School of Biosystem and Environmental Engineering
TGL	Total Grain Loss
USDA	United States Department of Agriculture

LIST OF NOMENCLATURES

a_1	Centreline distance between the rods
a_2	Rod diameter
a	Acceleration
β	Crop moisture content on dry basis
b_1	Centreline distance between the bars
b_2	Width of the bar
C_c	Concave clearance
C_T	Throughput capacity
D_e	Effective diameter of the drum cylinder
D_L	Damage loss
d_1	Average size of the grain considered spherical
η_t	Threshing efficiency
E	Energy
F_r	Feed rate
F	Frictional force
G	Gravitational force
K_t	Threshing constant
K_e	Grain size constant
L	Length
L_c	Linear concave width
N	Revolution per minute
θ	Angle in radian

P	Power
P_r	Power required to run the cylinder
P_i	Power required to detach grains from the panicles
P_f	Power required to overcome friction
P_t	Power required to thresh beans
β	Bulk density
$p^{/}$	Probability of grain passage through the concave opening
Q	Crop mass feed rate
S	Crop stream thickness
S_n	Un-thresthed grain
S_f	Separation efficiency
T	Torque
T_L	Threshing loss
T_e	Threshing efficiency
t_d	Dwell time
T_c	Tension on tight side
T_s	Tension on the slack side
U	Initial velocity
μ	Coefficient of motion resistance of crop stream on the concave
v	Velocity
v_b	Velocity of the beater/peg
v_f	Linear velocity of the feeder
v_c	Velocity of the crop
T_L	Threshing loss

W	Width of the thresher
$\mathbf{W_d}$	Mass of dried material
$\mathbf{W_w}$	Mass of wet material
Y	Radius driven by the pulley of the cylinder
ʎ	Space increment between respective successive events
Z	Grain straw ratio

ABSTRACT

In Kenya, threshing of common beans at smallholder level is mainly by traditional methods using sticks and animal trampling which are slow, inefficient and tedious. Combine harvesters are suitable for overcoming such difficulties. However, the existing economic structure of agricultural production coupled with the small size of farms in Kenya makes the use of combine harvesters uneconomical. Portable threshers offer an alternative solution to threshing of beans for smallholder farmers, but they are rare in the local market. Therefore, this study focussed on development of a portable common beans thresher that is customized to the needs of small-scale famers (working up to 10 ha). The design process was through modelling, simulation, optimization and fabrication of the thresher. The mathematical models of the machine were developed by dimensional analysis through the concept of Buckingham pi theorem and reference to other similar work in literature. The objective function for optimization involved minimizing grain damage and power required for threshing while maximizing threshing efficiency and throughput capacity of the machine using Taguchi method. The results from simulation and experiments show that there were strong to very strong correlations between simulated and actual data as the coefficients of determination were greater than 0.7. The differences between the means of the simulated and actual data were not statistically significant at 5% level of significance for power requirement and throughput capacity. A prediction performance of 77% was attained when actual and simulated data were compared at 10% absolute residual error. It was observed that power requirement, bean grain damage, threshing efficiency and throughput capacity increased with increase in pegs peripheral speed from 1.88 m/s to 5.65 m/s for actual and simulated data. The optimum mean values for bean grain damage of 1.73%, threshing efficiency of 99%, throughput capacity of 57.95 kg/hr and power requirement of 556.6 W were obtained at 3.765 m/s peripheral speed of pegs, 0.023 kg/s feed rate, 1 m linear concave width, 17.5% moisture content (w.b) and 5.5 kg weight of threshing cylinder. Threshing efficiency of 99% was achieved for the developed bean thresher for all cylinder rotational speeds greater than 600 rpm. The thresher attained throughput capacities of 72 and 125 kg/hr at feed rates of 1 and 2.5 kg/min, respectively. Mechanical bean grain damage was less than 3.3% for cylinder rotational speeds of 600-1000 rpm. In addition, the beans thresher consumed one litre of petrol to thresh 30 kg of beans. Finally, the thresher had a cleaning efficiency of 78.7% at optimum cylinder rotational speed of 800 rpm. The developed common beans thresher may require improvement on cleaning efficiency and automation, otherwise it is recommended for use by the small-scale bean farmers.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Common bean (*Phaseolus vulgaris L*), also referred to as dry bean is an annual leguminous crop. Among major food crops, it has one of the highest levels of variation in growth habit, seed characteristics (size, shape, and colour), maturity, and adaptation. It also has a tremendous variability with over 40,000 varieties. It is prime staple food in Eastern and Southern Africa where it is recognized as the second most essential dietary protein and third most important source of calories (Wortmann, 1998).

Common bean is rich in the essential amino acid element lysine, which is found in fewer quantities in maize and other grains (Mutuku *et al.,* 2018). It is also an appetite suppressant because it digests slowly and causes a low sustained increase in sugar levels hence good for weight reduction. As a result, health organizations are promoting regular consumption of common bean and other pulses. It has been found to reduce the risk of diseases such as cancer, diabetes or coronary heart diseases (Mudryj *et al.,* 2014).

The crop is grown in almost all regions in Kenya mainly intercropped with maize. However, Eastern, Nyanza, Central, Western, and Rift Valley are the major bean-growing regions (Wortmann, 1998). Historically, beans have been grown for sustenance; however, they have become an important source of income for small-scale Kenyan farmers. This is because of the increase in population resulting to increase in demand of common beans of over one million metric tonnes annually against production of 750,000 tonnes in Kenya. The use of traditional human power coupled with a minor subdivision of land are the major reasons for low production. Therefore, farm mechanization is key towards smart, efficient farming to improve beans production in Kenya (Groote *et al*., 2020).

Globally, common bean is produced in a range of crop systems and environments in regions as diverse as Latin America, Africa, the Middle East, China, Europe, the United States, and Canada. The leading bean producer and consumer is Latin America, where bean are a traditional, significant food, especially in Brazil, Mexico, the Andean Zone, Central America and the Caribbean (Pachico, 1989). For the poor of the world, beans are a means of keeping malnutrition at bay. Therefore, any advances in scientific research that benefit bean yields, particularly in developing countries, helps to feed the hungry and give hope for the future (Beebe *et al.*, 2012).

Common bean postharvest practices include threshing, drying, cleaning, packaging and storage (Uebersax *et al*., 2022). Once harvested, the bean plants are either left in the field or taken elsewhere to dry. Bigger producers use drying silos or dryers designed for sacks before they are threshed. (Mutungi *et al.,* 2022). Threshing methods vary widely (Muasya, 2001). Large-scale producers use moving machinery which are suitable for large scale farms in developing countries Kenya included (Alarakhia, 1972). However, the existing economic structure of agricultural production, coupled with small size of farms in developing countries make the use of grain combine harvesters uneconomical. The intercropping of beans and maize by farmers also make them unsuitable for use (Opole *et al.*, 2003)

Traditional methods of threshing are the most common in Kenya, However, these methods result to contamination of the product with stones, sticks, chaff, dirt and dust (Katungi *et al*., 2009). Therefore, bean grains, after threshing cannot be stored or used for consumption unless they are cleaned. This is as a result of foreign materials present in the grain that accelerate deterioration leading to poor physical condition and quality of grains (Sangakkara, 1988). Consequently, farmers are compelled to do additional work of separating and cleaning to maintain quality and the value of the produce prior to storage, marketing, distribution and subsequent processing. However, it is labour intensive, inefficient, time consuming and high costly operations (Benaseer *et al*., 2018).

The solution to threshing problems facing small scale bean farmers can be addressed by portable threshing units with higher throughput capacity compared to traditional methods and are less expensive compared to heavy combine harvesters (Olaoye *et al*., 2010). Portable common beans thresher is rare in Kenya because of the delicate nature of beans grains that require an understanding of machine and crop characteristics (Ndirika, 2006). Grain damage caused by impacts of the moving parts of crop threshing units and incorrect clearances between the stationary and moving parts of the units are some of the concerns to bean farmers and consumers (Ukatu, 2006). Higher thresher unit rotor speeds favour higher threshing efficiencies, throughput and output capacities; but results in an increased seed damage as high as 40-50% (Bunyawanichakul *et al.*, 2007). There is also a problem of separation of the seed from the straws which is related to concave sieve sizes (Osueke, 2011 and Mutai, 2018). Therefore, this study focussed on the development and evaluation of portable common beans thresher

The design and development of cereal grain threshers is not entirely a new area of study. Various cereal stationary threshers exist for different crops like sorghum, rice, cashew nuts, and millet. However, there is scanty information on common beans thresher. Reported findings have mainly focused on experimental data and few theoretical modelling of the threshing unit (Desta and Mishra, 1990). To understand the effect of machine and crop parameters on performance of common beans thresher, simulation is necessary using a mathematical model. Modelling and simulation is the use of physical, mathematical, or logical representation of a system or process to generate performance data (Law *et al*., 2000).

Simulation can be achieved by setting up a model of a real system and performing experiments on it for design and evaluation. Softwares like Visual Basic and Python can use mathematical model equations for simulation (Dysarz, 2018). Researchers have in the past used these softwares to simulate the performance of machines before full-scale development and, after that, only construct the most promising design. Osueke (2011) simulated operating parameters using visual Basic computer-aided software to determine and identify the performance characteristic of least threshing loss due to grain damage, incomplete threshing, and threshing efficiency. In this study, Python was selected because it is free and open-source, object-oriented, simple and easy to use, has many libraries including Numpy, Scipy, and Sympy for manipulating mathematical and numerical expressions, constants, and multi-dimensional matrices (Hart *et al.*, 2011).

Some of the important common beans and machine variables include moisture content, bulk density, pegs peripheral velocity, concave clearance, concave width and mass of the threshing cylinder (McDonald & Copeland, 2012). Variation of the mentioned variables results in different outputs of threshing efficiency, power requirement, throughput capacity, and grain damage. This, therefore, creates an optimization problem to be solved for efficient machine functioning. In this study, Taguchi technique was used for optimization. Several other optimization techniques used by researchers include mathematical methods by use of calculus, linear, nonlinear, dynamic, geometric, separable, and quadratic programming (Rao, 2019). The development of common beans thresher was a process of modelling, simulation, optimization and fabrication.

1.2 Problem Statement

In Kenya, post-harvest losses are reported at 20% for cereal grains (Tefera, 2012). Threshing is one of the primary agro-processing practices that contributes to post-harvest losses (Kiaya, 2014). The conventional threshing methods involve beating them with a rod or stick and animal treading, which are tedious, inefficient, time-consuming, and require much energy to the extent of causing blister. Grain combine harvesters were made to overcome such difficulties associated with the traditional method of threshing harvested beans. However, the existing cost-effective structure of agricultural production and the small scale of farms in Kenya make their use uneconomical. The traditional threshing of common beans problem can therefore be addressed by portable threshers; however, they are rare in the market hence the need for development and evaluation.

Grain damage caused by impacts of the moving parts of crop threshing units and incorrect clearances between the stationary and moving parts of the units are some of the concerns to bean farmers and consumers (Ukatu, 2006). In addition, higher thresher unit rotor speeds favour higher threshing efficiencies, throughput and output capacities; but results in an increased seed damage as high as 40-50%

(Bunyawanichakul *et a*l., 2007), making this an optimization problem. There is also a problem of separation of the seed from the straws which is related to concave sieve sizes.

Finally, inadequate information is available about the effect of common bean characteristic, machine and operational parameters in relation to the performance of the threshing unit. Therefore, bean variety, moisture content, feed rate, cylinder peripheral speeds, concave configurations and clearance have to be studied. Simulation of threshing and separation process, threshing loss and grain damage will provide a better understanding of the fundamental relationship of different machine and crop characteristics in order to identify the contribution of each variable.

1.3 Objectives

1.3.1 General Objective

To optimize design parameters and performance of a portable common beans (*Phaseolus vulgaris L.*) thresher.

1.3.2 Specific Objectives

1. To simulate the effect of design variables on performance of a portable common beans (*Phaseolus vulgaris L.*) thresher.
2. To optimize design parameters and performance of a portable common beans (*Phaseolus vulgaris L.*) thresher.
3. To develop and evaluate the performance of the optimised portable common beans (*Phaseolus vulgaris L.*) thresher.

1.4 Research Questions

i. How does a portable common beans thresher perform based on simulated design variables?
ii. What are the optimal design factors that results to optimal performance of a portable common beans thresher?

iii. How does the developed optimized common bean thresher perform under different drum speeds?

1.5 Justification

Food security is among the "Big Four Agenda" which is an economic blueprint that was developed by the government of Kenya in 2017. It was meant to foster economic development and provide solutions to various socio-economic problems facing Kenyans. This is also included under zero hunger in the new sustainable development goal two. Common bean (*Phaseolus vulgaris* L.) is a major staple food in Eastern and Southern Africa where it is recognized as the second most important dietary protein and third most important source of calories (Wortmann, 1998). Therefore, this study on mechanization common beans threshing process to enhance production is in line with the global and national Agenda.

It is also important to note that common beans for the developing nations, are a means of keeping malnutrition at bay. As a result, health organizations fronted by World Health Organization are promoting regular consumption of common bean and other pulses. This is because it has been found to reduce the risk of diseases such as cancer, diabetes or coronary heart diseases (Leterme, 2002). Therefore, any advances in scientific research that benefit bean yields, particularly in developing countries, will help to feed the hungry and give hope for the future (Beebe *et al*., 2012).

The outputs of traditional threshing methods are low, resulting to delays in handling of large volumes of produce. This not only ensue losses but also makes the cost of operation to be quite high. These difficulties could be solved by engine powered threshers such as grain combine. However, the existing small size of farms in developing nations, Kenya included makes their use uneconomical. Portable threshers would otherwise provide solutions although with challenges that requires improvement.

Areas that need to be addressed through scientific research in stationary thresher include; Seed damage caused by impacts of the moving parts of crop threshing units and incorrect clearances between the stationary and moving parts of the units;

problem of separation of the seed from the straws and very little information is available about the common bean characteristic, machine and operational parameters in relation to the performance of the threshing unit. Therefore, bean variety, moisture content, feed rate, cylinder peripheral speeds, concave configurations and clearance have to be studied and optimized. Modelling of threshing and separation process, threshing loss and grain damage will provide a better understanding of the fundamental relationship of different machine and crop characteristics in order to identify the contribution of each variable for optimization.

1.6 Scope and Limitation of the Study

This study was confined and limited to development of mathematical models relating to design parameters and performance of a common bean (*Phaseolus vulgaris L.*) thresher, development of a computer simulation program, optimization of the design parameters and performance of a common bean thresher, development of an optimized solar thresher and evaluation of its performance when threshing common beans. The study was conducted in Jomo Kenyatta University of Agriculture and Technology (Juja Kenya at coordinates of 1.0912° S, 37.0117° E), However, fabrication and data collection were done at Egerton University (Nakuru Kenya at coordinates 0.3714° S, 35.9410° E) workshop. The beans variety used in evaluation of the thresher was the red kidney type commonly known as “Nyayo” in Kenya. The type of threshing mechanism used in this study was spike or peg tooth cylinder. Modelling was based on python programming language. Finally, cost-benefit analysis of the developed thresher was not under the scope of this research as well as optimization of cleaning efficiency.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background on Common Beans

Phaseolus vulgaris L, also known as the common bean is herbaceous annual plant grown worldwide for its edible dry seeds or unripe fruit commonly called beans (Oraibi *et al*., 2015). The main categories of common beans, on the basis of use, are dry beans which are seeds harvested at complete maturity, snap beans from tender pods with reduced fibre harvested before the seed development phase and threshed beans from seeds harvested at physiological maturity. Its leaf is also occasionally used as a vegetable and the straw as fodder (Gentry and Scott, 1969). It has one of the highest levels of variation in growth habit, seed characteristics in terms of size, shape, colour, maturity, and adaptation. It also has a tremendous variability (> 40,000 varieties). They are appreciated throughout the developing world because they have a long storage life, good nutritional properties and can be easily stored and prepared for eating (Adeyemi, 2020).

Common bean contains high protein content, source of energy, provides folic acid, dietary fibre, and complex carbohydrates (de Almeida Costa *et al.*, 2006). The grain legume is predominantly grown in Eastern and Southern Africa and its consumption is statistically high relative to other types of protein like meat simply because of its availability and cost. Albeit the existence of other related functions for the poor, evidence abounds as reported by de Almeida Costa *et al.* (2006), that common beans play a strategic and overarching role in alleviating malnutrition especially among the poor. Regular consumption of common bean and other pulses is now promoted by health organizations because it reduces the risk of diseases such as cancer, diabetes or coronary heart diseases (Leterme, 2002). This is because common bean is low in fat and is cholesterol free. It is also an appetite suppressant because it digests slowly and causes a low sustained increase in blood sugar. Researchers have found that common bean can delay the reappearance of hunger for several hours, enhancing weight-loss programs (Montoya *et al.*, 2010).

Phaseolus vulgaris L is produced in a range of crop systems and environments in regions as diverse as Latin America, Africa, the Middle East, China, Europe, the United States, and Canada (Schwartz and Corrales, 1989). As discussed in the introduction section, the leading bean producer and consumer is Latin America, where beans are a traditional, significant food, especially in Brazil, Mexico, the Andean Zone, Central America, and the Caribbean. In Africa, beans are grown mainly for subsistence, where the Great Lakes region has the highest per capita consumption in the world (Kamonzo *et al*., 2018). Beans are also major source of dietary protein in Kenya, Tanzania, Malawi, Uganda, and Zambia. In Asia, dry beans are generally less important than other legumes, but exports are increasing from China (Katungi *et al*., 2009).

In Latin America, Africa and Asia, common beans are primarily a small-scale crop grown with few purchased inputs, subjected to biological, edaphic and climatic problems (Beebe, *et al.,*2012). Beans from these regions are notoriously low in yield, when compared to the average yields in the temperate regions of North America and Europe (Abdelwahab, 2006). The production is however manual by use of hand and animals (De Groote *et al*., 2020). Mechanization of common beans production will not only increase production in Kenya but also reduce losses, especially during post-harvest practices. Beans are nearly a perfect food. Nutritionally rich, they are also a good source of protein, folic acid, dietary fibre and complex carbohydrates (Hayat, 2014). Further, when beans are part of the normal diet, the use of maize and rice proteins increases since the amino acids are complementary. Beans are also one of the best non-meat sources of iron, providing 23-30% of daily recommended levels from a single serving (Shimelis and Rakshit, 2005). Therefore, any advances in scientific research that benefit bean yields, particularly in developing countries, will help to feed the hungry and give hope for the future.

Cultivation of common beans in Africa is widespread, but its production is rigorous and mostly concentrated in Eastern and Southern Africa across 10 countries. In terms of acreage of common bean in Africa as per the FAO statistics, Kenya was the leading producer at 910478 Ha closely followed by Uganda (794375 Ha) and then Tanzania at 373125 Ha (FAOSTAT at www.fao.org) by the end of 2007. Among the top producers, Malawi and Ethiopia, rank eighth and ninth, respectively. However, in terms of productictivity, Kenya at 412381 tons came second after Uganda, at 478625 tons with Tanzania at 285414tons keeping its third position. Common bean yields are higher in Uganda than in Kenya because of a relatively favourable biophysical environment such as weather condition in Uganda compared to Kenya. In the latest figures from Food and Agriculture Organization (FAO) for 2007 on the website, however, the average production in Kenya has skied above 500,000 tonnes (Mutuku *et al*., 2018).

In Kenya, the crop is the most important pulse and ranks second after maize as a staple food crop grown by more than three million households. Beans in Kenya is also a main contributor to nutrition, food security, income, and employment (Maingi *et al*., 2001). They are applauded as a strategic remedy for hidden hunger and healthy eating. It is most important for children and women of reproductive age. This is because bean is an excellent source of cholesterol-free dietary proteins, energy, folic acid, fiber, and micronutrients (iron and zinc). When compared with meat, beans are a low-cost protein alternative to lowly endowed segments of the community. Thus, they are considered poor man's meat (Barman *et al*., 2018). Therefore, any research towards increasing beans production is highly encouraged.

Historically, common beans have been grown for sustenance, however, they have become an important source of income for small Kenyan farmers (Katungi *et al.*, 2010). This is because of the growing consumption demand of over one million metric tonnes against an average production rate of 600,000 metric tonnes (Van Loon *et al*., 2018). The majority of the producers of common beans in Kenya are small-scale farmers due to the existing economic structure of agricultural production characterized by small farm sizes. This could be extended given its short growth cycle of approximately 70 days (Katungi *et al*., 2010), which is resilient to erratic rainfall patterns. The short duration allows the marketing of beans which provides income to the household and food to the consumer before harvesting other longseason crops such as maize. The production is however by use of hand and animals (De Groote *et al.*, 2020).

Mechanization of common beans production will not only increase production in Kenya but also reduce losses, especially during post-harvest practices (Manandhar *et al.*, 2018). Figure 2.1 shows statistic of beans production in Kenya in the year 2005 to 2019. The data indicates intermittent growth in production of beans. By the year 2019, the production was at 747,000 tonnes against a consumption of over a million tonnes. This is an indication of demand for commercial production of beans in Kenya to supply in the local market as well as international. A number of factors have contributed to the slow growth of beans production in Kenya. Poor land use policy on subdivision of agricultural land, climate change, expensive farm inputs and low mechanization are some of the key factors in Kenya.

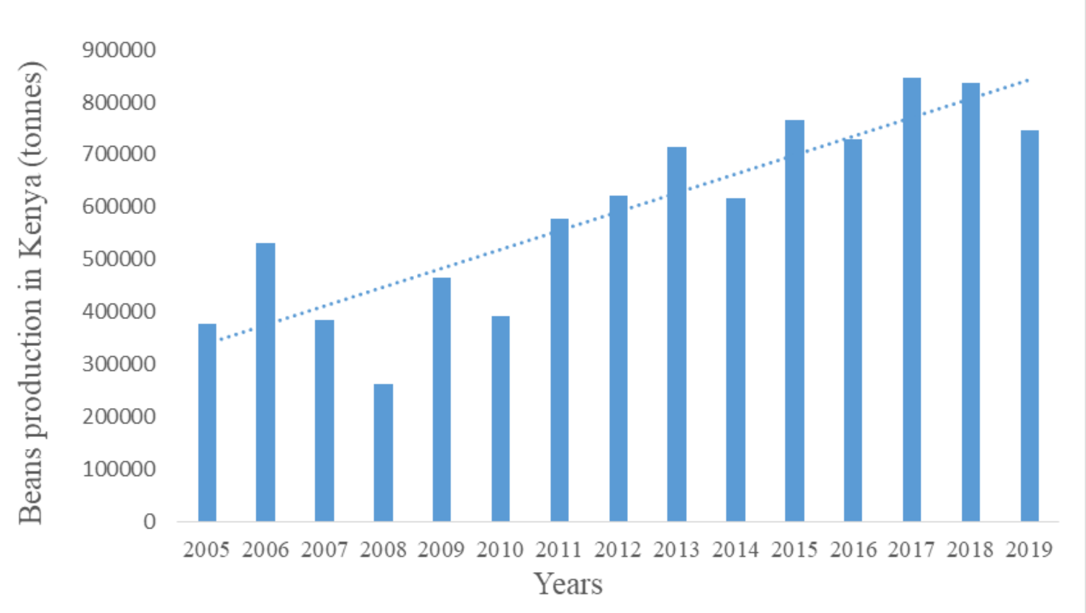


Figure 2.1: Beans production in Kenya in the years 2005 to 2019.

Source: FAOSTAT at www.fao.org

Common bean production in Kenya is mainly in highland and midlands. About 75% of the annual cultivation occurs in three regions namely; Rift Valley, Nyanza, and Western Provinces. In terms of output, Rift Valley contributes the biggest share, accounting for 33% of the national output followed by Nyanza and Western provinces accounting for 22% each. Output from Eastern parts of the country and the Coast is constrained by adverse climatic conditions (Katungi *et al.*, 2011).

An impressive high diversity of about 80 different seed types of common bean has existed in Kenya since the late 1970s (Katungi *et al.*, 2009b). Of these, six seed types including; Red and red/purple mottled occurring in different local names such as Rose coco, Nyayo, Wairimu, Kitui among others, Purple/grey speckled locally known as Mwezimoja and Pinto sugars locally known as Mwitemania dominate (Blair *et al.*, 2009). Rose coco is the most widely grown followed by Canadian wonder. Rose coco and Canadian wonder type as argued by Blair *et al.* (2009), are high yielding but flourishes under high soil fertility and heavy rains to give good yields. Due to the continued deterioration of soil fertility and persistent bean associated pests and diseases, these varieties continue to lose area and are consequently being replaced by varieties like the red haricots that are well adapted to poor soil conditions and large Pinto “sugar bean” locally called “Surambaya” and (Katungi *et al.*, 2011).

2.2 Threshing of Common Beans

Threshing is the process of separating the grain from the seed panicles (Ani *et al.*, 2017). The process involves loosening the edible part of cereal grain from the scaly chaff that surrounds it through the application of tensile, compressive, bending and twisting forces on the grain heads (Simonyan & Yiljep, 2008).Threshing originally meant the simple operation of knocking grain free from the ears, but the term now embraces the processes of separating the grain or seed from its straw, and chaff, freeing it from impurities and grading it ready for use.

Pre-harvest processes are diverse. Developed countries use highly mechanized techniques for production of beans (Delgado *et al*., 2017). In Latin America, except Argentina where beans are produced on large holdings with high technical input, small scale farmers are the main bean producers. Mexico, Brazil, Chile, and Cuba have three types of bean producers, large scale, medium scale and small-scale. Colombia, Venezuela, Dominican Republic, Peru, Guatemala, and Costa Rica have limited areas of large-scale which is highly mechanized (van Schoonhoven & Voysest, 1989). In the case of mechanized harvesting, bean plant needs to be uniform and upright with pods off the ground. Breeding for an improvement in plant architecture would help mechanized harvesting become more efficient and cut down on losses. At harvest, the variety needs to be ready all at the same time. If plants are too mature pods open.

Once beans are harvested and separated from the plant, the bean seed continues to ripen, thus biochemical reactions occur, which deteriorate the quality (Uebersax *et al*., 2022). Therefore, at harvest, humidity content, temperature, and climate effect need to be controlled to carry out bean threshing. There are two types of mechanized dry bean harvesting: conventional undercutting, rodding, or winnowing then combining; and the direct harvest system requiring only one pass of the combine (Almirall *et al*., 2010). The latter system has some problems associated with it, such as high header losses and the difficulty of threshing immature plants and weeds. The reduced harvest cost, and lower risk from high winds and water staining are some of advantages of mechanization. Moisture levels should be about (13 -15 %) on wet basis. Depending on the size and type of machinery used, 1 hectare of beans may be harvested in 1-2 hours (CIAT, 1999).

In developing countries, Kenya included, harvesting is mostly manual. Plants are pulled up and placed in rows in case threshing machine is used, or in piles very early in the morning to avoid pods opening (Sandhu *et al*., 2018). When harvesting is done totally by hand, 1 hectare requires 50–80-man hours. Climbing species have to be harvested pod by pod as they mature upwards. Humidity should be about (12-13%) (CIAT, 1995). Careful harvesting is important to the bean yield. Mistakes at this point could undo all the benefits of earlier proper practices. Small-scale farmers need equipment they can use in their fields, thus small-scale technology needs to be developed which is the main focus of this study. As discussed in the introductions section, threshing of common beans can be done using manual traditional methods, small engine driven threshers or by use of heavy combine harvesters.

2.2.1 Manual threshing

Nearly all small-scale farmers in the developing countries harvest their bean by hand and thresh them later. Beating with stick and bullock treading of the harvested common bean has been the traditional method of threshing. Though these methods outwardly seem to be cheap and simple, it is repeatedly stated in literature that they are wasteful in that they inevitably cause considerable grain loss and damage, besides being slow and cumbersome. In some cases where threshing floor is not carpeted, resultant threshing material is reported to be contaminated with foreign material such as small stones and dust particles (Sangakkara, 1988). Figure 2.2 shows threshing by hand commonly practiced in Kenya. The beans are harvested, dried, threshed, cleaned and packaged manually.

Figure 2.2: Manual threshing by hand using sticks.

Source: https://www.bing.com/images/

2.2.2 Mechanical threshing

Mechanical threshing concept involves providing energy for turning materials, drawing in materials to be threshed and creating velocity of different layers to rub grain heads together. The grain separating process directly acts on the linkage of grain and stalk. According to Joshi *et al.*,(1981), mechanical threshers comprise hopper, threshing chamber, cleaning unit and outlets for grains and chaff (Olaoye *et al.*, 2011). Engine powered mechanical threshers are considered more advanced compared to manually powered ones.

The threshing chamber is made of a drum and concave. The drum beats the panicles of the crop against stationary concave and forces out the grains from the panicle. The drum consists of a long cylindrical shaped member mounted on bearings to which a series of pegs or rasp bars are attached on the surface. The concave is perforated to enable the threshed product to drop by gravity into a collector (Schloesser, 1998).

A study of literature on threshing mechanisms revealed that over a number of years, the engineers working in various sectors of the world have designed and developed numerous threshing mechanisms for doing the simple job of knocking out grains from ear or pods. The working principles of some of these mechanisms, and their uses are discussed in the subsequent sections.

2.2.3 The cylinder/concave threshing mechanism

The cylinder/concave mechanism shown in Figure 2.3 is by far the most commonly used of all other mechanisms. Its universal adoption appears to be as a result of its ability to thresh a wide range of crops and high threshing efficiency with a low degree of injury to the seeds if used skilfully. In addition it is easy to maintain continuity in feeding and it is easy to feed into this mechanism (Huynh *et al.*, 1982).

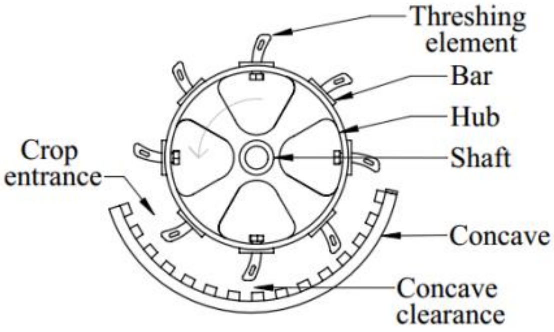


Figure 2.3: Cylinder/concave threshing mechanism.

Source: Ndirika (2005)

Two components constitute this conventional threshing mechanism namely; a cylinder/or drum and a concave. The concave which is located below or above the cylinder is curved inwards and surrounds about one quarter of the cylinder circumference; hence, it is name "concave" (Ramteke & Sirohi, 2003). Removal of seeds from the heads or pods is ordinarily accomplished with rotating cylinders. The threshing action of this cylinder is primarily derived from the force of impact. Then the relatively slow-moving material comes in contact with the high-speed cylinder, the force of impact shatters the heads or pods and frees a considerable portion of the grain from the straw (Ndirika, 2003). Further threshing is obtained by the rubbing action as the material is accelerated and passes through the restricted clearance space between the cylinder and the concave.

The threshing mechanism, since its first appearance, has constantly been subjected to modifications with an aim of perfecting its performance and as a result it is now available in varying designs (Dion, 1952). The designs include; Spike tooth or peg tooth cylinder, Rasp Bar Cylinder Concave, Angle Bar Cylinder.

2.2.3.1 Spike or peg tooth cylinder mechanism

The spike or peg tooth cylinder as indicated in Figure 2.4 is the oldest type of threshing mechanism (Wolgast, 1956).

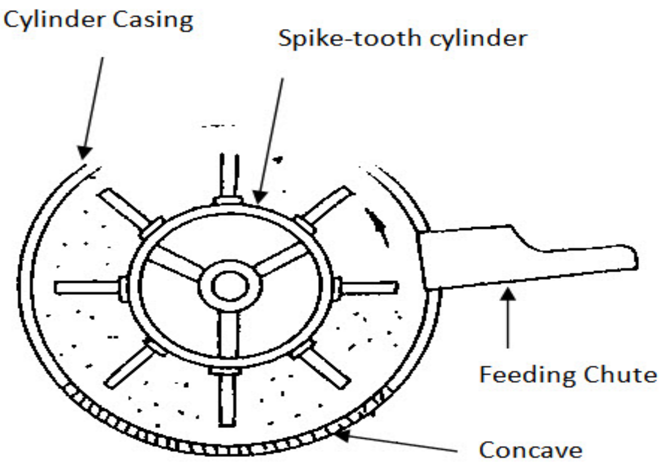


Figure 2.4: Spike or peg tooth cylinder mechanism.

Source: Alarakhia (1972)

It has heavy steel teeth or pegs bolted to the periphery of the drum and to the inside of the concave. The arrangement of the spike tooth cylinder and concave is such that the cylinder teeth pass midway between staggered teeth on the concave, or vice versa thus producing a combing action (Lohan, 2007). Provision is usually made for control of the overlapping of the cylinder and concave teeth (Concave, 1969). The shape and size of the teeth vary somewhat depending upon a particular design. Some have rounded teeth, others possess tapered teeth. The teeth in the concave are mounted on perforated or solid removable sections. The total number of rows of teeth needed in the concave usually two; four or six depends upon the crop and the threshing conditions. Teeth with corrugated sides are sometimes installed for difficult threshing conditions (Krishnan *et al.*, 1994). Most of the pedal threshers used for threshing rice are equipped with the tooth peg type mechanism.

2.2.3.2 Rasp bar cylinder concave

The rasp bar cylinder concave mechanism has transverse bars with grooved metal faces as shown in Figure 2.5. These bars are parallel to the shafts and to each other. The grooves are out diagonally in opposite directions, across adjacent bars. Corrugated bars are occasionally used on the concave as well as on the cylinder. The evolution history of this mechanism shows that earlier models had flat solid bars (Harrison, 1969). Threshing is done by the rasping action between the cylinder bars of the drum and the concave.

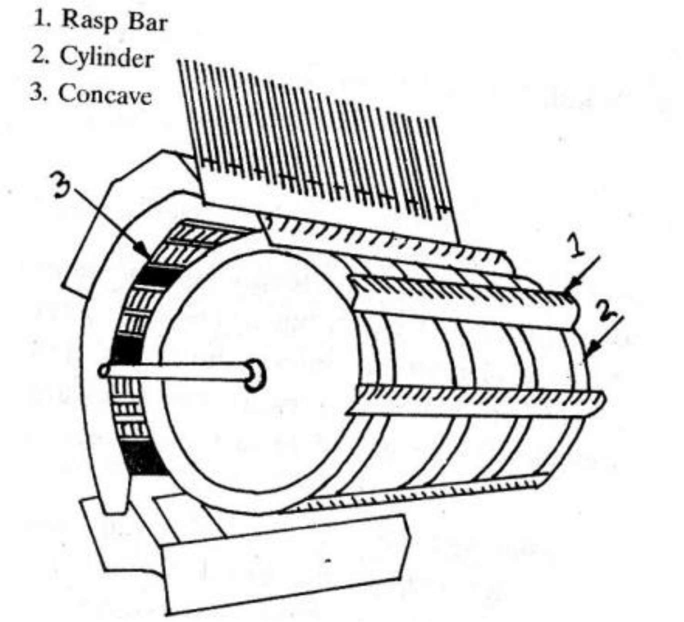


Figure 2.5: Rasp bar cylinder concave mechanism.

Source: Dhananchezhiyan *et al*. (2015)

2.2.3.3 Angle bar cylinder mechanism

The angle bar mechanism is equipped with helically, or straight mounted, rubber faced bars, the rubber being vulcanized to metal. The concave is ordinarily fitted with a rubber faced shelling plate and steel jackated rubber bars. The seeds are threshed by being flailed out between the revolving cylinder bars and the stationery shelling plate, and the steal jackated rubber bars. According to (Suleiman & Dangora, 2017) this mechanism only threshes by impact.

It does not seem to be as popular as the two mechanisms described earlier and hence failed to attract research interest. However, Klein *et al.* (1966) did detailed work to establish its optimum settings to combine harvest crimson clover. Based on flailing action mode, it does not appear to be harsh in its treatment of crops, and therefore it is a mechanism for threshing grain legumes. This is because they are susceptible to damage, if treated severely while threshing (Roberts & Arnold, 1966). Other designs of cylinder/concave threshing mechanisms include; tire loop cylinder, star and bar pattern maize cylinder, modified cylinder and concave mechanism.

2.2.4 Centrifugal threshing mechanism

The centrifugal threshing mechanism seems to incorporate a completely new principle for threshing and cleaning grains. Lalor and Buchele (1963) invented a threshing cone for centrifugal threshing (Lalor & Buchele, 1963). It was shown to reduce the impact level on grains and obtain threshing separation and cleaning in one process, unlike conventional threshing where the actual knocking out of grains from the ears and separation of the grain from the chaffs are two distinct processes. In this new thresher, however, the heads of the grains are taken into a conical cylinder in which a rubbing action in combination with a whirling movement separates the grains from the heads. The centrifugal force developed by this whirling action drives the grain to the screened cylinder wall; hence it passes through the screen, where a wind blast cleans the grain of any chaff that managed to get through the screen (Hamdy, 1965).

2.2.5 Fluted rim and rotating disc mechanism

Fluted rim and a rotating tooth disc mimic the hand peeling process of shelling kernels that comprises of rubbing together of two ears. Three components constitute the basic design of a hand maize sheller. Maize is shelled by pressing the cobs on the fluted rim, held in the required position by pressure from springs or in the absence of these springs, it is necessary to hand press the cobs to prevent them from jumping out during shelling. A toothed rotating disc peels off the kernels from the ears. However, the basic design in this mechanism does not suggest any potential to consider it for grain legume thresher development work (Deckler, 1997).

2.2.6 Rubber rolls and endless belt mechanisms

With grain legumes it is quite possible to split open the pods with squeezing action, a rubbing action or a joint action or both. Rubber covered steel rolls have been used to a limited extent for threshing beans. This mechanism at the outset seemed to be suitable for the peasant farmer since the peripheral speed required for threshing was low enough to be achieved with ease, for hand operation. However, a critical look into the mechanism showed two limitations for its wide adoption as a tool for the smallholder farmer. The cost involved in driving three rollers with gears may raise the final production cost, beyond what a peasant could afford. Secondly, for successful threshing the important criteria seemed to be that the pods ought to be sort of crisp dry before they would give up to this squeezing, rubbing action, and pop open (Mesquita & Hanna, 1993). Other threshing mechanism design is vibration threshing mechanism that involves revolving bars which cause the squeezing and rubbing action of the podded plants.

2.2.7 Common bean physical properties influencing threshability

Physical properties of common beans such as moisture content, bulk density, size of the grain and straw-grain ratio are necessary in the design of a grain threshing unit. The moisture content of grain which is determined using wet basis gives the safe range of efficient threshing and grain damage. According to Concave, (Concave, 1969) it was found that moisture content influences threshability and kernel damage. It was also noted that straw moisture content has greater effect on threshing performance than grain moisture content (Lin, 1977). It was reported by (Osueke, 2011) that there is a range of moisture content for which the threshing efficiency, grain damage and output capacity can be affected. Beyond this range any increase in moisture content had no significant effect on threshing performance parameters.

The bulk density which is the weight per unit volume of material is dependent upon the degree of packing. There is limited information in literature on how it affects threshability and grain damage. However, bulk density is important in determining thresher output capacity and cushioning effect of the material in the cylinder-concave unit (Simonyan *et al.*, 2006). The straw grain ratio is found by weighing the straw and grain separately after separating the grain from the stalk head or ear head. It is useful in the determination of the thresher output capacity (Maertens & De Baerdemaeker, 2003). The size of the grain helps in deciding the distance between the rods in the cylinder concave assembly (Miu & Kutzbach, 2008a). It is found by measuring the length, width and thickness of the grain.

Goss *et al*. (1958), found that at a given feed rate of straw and chaff only, an increase in straw grain ratio caused increase in shoe free seed loss (Shandilya, 1987). Although the effect was usually small, increased feed rate tends to reduce seed damage. Dodds (1968) reported that with an increase in feed rate the power requirement at the main shaft increased (Kumar *et al.*, 2016). The spike toothed cylinder required less power and had more positive feeding action than the rasp bar cylinder.

2.2.8 Machine characteristics influencing threshability

Machine parameters that include feed rate, concave clearance, cylinder threshing speed, cylinder diameter, cylinder width and concave length affect the performance of a thresher, hence are key in design. Vas and Harrison (1969) reported that cylinder speed was the primary influencing parameter, while concave clearance, although of less significance, was an important factor as well. The effect of feed rate, cylinder speed and concave clearance on threshing was described based on impact model.

An increase in feed rate resulted in a decrease in mechanical damage which was described as a result of cushioning effect at higher feed rates. This cushioning did not affect the threshability which should have decreased in reality. Since it was not supported by results, a frictional model was developed. According to this model, increased feed rate might have increased the crop stream density which in turn increased frictional forces between particles in the crop stream. Thus the cushioning effect of the impact model may have tended to decrease the threshability but was restricted by the frictional model on threshability (Harrison, 1969).

The rubbing effect of the frictional model would not result in damaged kernel. In conclusion, the effect of cylinder speed, concave clearance and feed rate on threshability and grain damage may be described on the basis of an impact model. These three parameters were confirmed to cause significant variation in percentage mechanical damage(Huynh *et al.*, 1982).

Klein and Harmond (1966) studied the effect of varying cylinder speed and clearance on three different threshing cylinders. They tried to determine cylinder type and its setting for efficient threshing without increasing the broken and damaged grain. The cylinders tested were: spike- toothed, rubber covered angle bar and rubber covered flat bar. Their optimum peripheral speed and clearance were 25.75 m/s and 0.40 cm; 20.9 m/s and 0.40 cm; and 24.53 m/s and 0.08 to 0.32 cm, respectively. The rubber covered flat bar cylinder recovered about 10% more crimson clover seed than the two cylinders and unthreshed seed loss was reduced to about 5% in the process (Klein & Harmond, 1966).

Tandon *et al*. (1988) used the step-wise multiple regression technique to study the relationship between different independent variables, namely, cylinder types, concave clearance, cylinder peripheral speed and moisture content in relation to the two dependent variables, namely, threshing efficiency and invisible grain damage on pulse grains (Qian *et al.*, 2017). An experimental model of pulse thresher without a cleaning and separating unit was developed. It has the provision to change the machine and operational parameters. The moisture content was found to have a significant effect on threshing efficiency and invisible grain damage. The effect of concave clearance and cylinder peripheral speed, though numerically small, was significant at 5% level (Sessiz *et al.*, 2007).

Singh and Bachchan (1981) reported the effect of crop and machine parameters on threshing effectiveness and seed quality of soya bean. The effect of moisture content, threshing speed and length of storage period after threshing, on threshing performance and quality of two varieties of soya bean were studied. It was found that unthreshed grain increased with increase in pod moisture content. The percentage of unthreshed grain decreased with an increase in cylinder speed for all pod moisture contents. The variety Ankur was a little harder to thresh and was more resistant to damage than PK 71-21. Both storage time and threshing speed had only a small effect on the germination percentage of both varieties (Singh & Singh, 1981).

2.3 Models for Grain Threshing

Modelling involves writing of equations to describe and predict the performance of a system both as functions of changes in inputs and as functions of the changes in the systems. In this study, the common bean and machine parameters will be necessary in developing the required equations (Pohl, 2010). Modelling of the threshing and separation process would provide a better understanding of the fundamental relationship of different machine and common beans characteristics in order to identify the contribution of each variable. This can be achieved by use of prediction equations to identify independent variable in the order of their contribution to the total variation on the dependent variables (Ndirika, 1997).

Miu (2002) developed a universal mathematical model for grain threshing and separation. The distribution frequency of unthreshed grain percentage into the threshing space is a continuous variable. At the end of the threshing space, L for axial unit, the unthreshed grain becomes threshing loss, V_t (%) (Miu & Kutzbach, 2008b), as presented in Equation 2.1. In the equation, Sn is percent of unthreshed grain and ƛ is space increments between respective successive events.

$$Vt = Sn(L) = e^{-\lambda L} \tag{2.1}$$

Enaburekan (1994) developed mathematical and optimization models for the threshing process in a stationary grain thresher using wheat and sorghum. One of the models developed for threshing efficiency (E_t) is shown in Equation 2.2:

$$Et = 1 - e^{-3K_T e(1-\alpha)VWDL/2QC} \tag{2.2}$$

In the equation, K_T is threshing constant, ρ is crop bulk density (kg/m^3), α is crop moisture content (%, dry basis), V *is* velocity of threshing cylinder (m/s), W is width of thresher (m), D *is* effective cylinder diameter (m), L *is* concave length (m), Q *is* crop mass feed rate (kg/s) and C *is* concave clearance (m).

Ndirika (1997) developed mathematical and optimization models for the threshing process in a stationary grain thresher using millet and sorghum. Equation 2.3 presents the threshing model that was developed.

$$T_e = 1 - e^{\frac{-1.5Kt\ell dDVbLc}{(1-\beta)Fr}} \tag{2.3}$$

In the equation, *Te* is threshing efficiency parameter (%), *Kt* is threshing constant, ρ is bulk density (kg/m^3), *Vb* is cylinder velocity (m/s), *Lc* is concave length (m), *Fr* is feed rate (kg/s), *D* is cylinder diameter (m) and β is moisture content (%, dry basis).

Huynh *et al*. (1982) stated that the rate of detachment of grains from their bindings is proportional to both the specific energy input to the crop and transmissibility of the energy across the length of the crop mat. The mathematical expression is given by Equation 2.4:

$$\lambda = K_T(\ell V_2^2 WD)/QC \tag{2.4}$$

In the equation, *D* is drum diameter, *c* is concave clearance, ρ is bulk density of crop, V_2 is peripheral velocity of rasp bar, *w* is width of thresher, *Q* is mass feed rate of crop and K_T is threshing factor.

2.4 Simulation of Design Parameters and Performance of Thresher

To understand the effect of machine and crop parameters on performance of common beans thresher, simulation is necessary using a mathematical model. Modelling and simulation is the use of physical, mathematical, or logical representation of a system or process to generate performance data (Law *et al*., 2000). Muna *et al.* (2016) developed threshing efficiency and optimization models for spike tooth mechanical cereal threshers using dimensional analysis and predictive validation methods. The model was fit when the threshing speed was in the range of 14.3 to 20 ms^{-1}, the feed rate was in the range of 0.1 to 0.2 kgs^{-1}, and moisture content was 10.6 to 15.8 % wet basis. Experimental data used for validation was from millet crop thresher, and the mechanical damage model was not developed, which is a cross-cutting issue in various studies. Comprehensive modelling and simulation of rasp bar cereal thresher were also presented by Osueke (2011). Threshing efficiency, power requirement, threshing loss, and grain damage models were developed. However, the model was validated with published threshing performance data, which was not clear on the type of crop. The established results were found to fit well, taking R^2 values equal to or greater than 0.9, which were highly significant ($\alpha=0.05$).

Simulation can be achieved by setting up a model of a real system and performing experiments on it for design and evaluation. Softwares like Visual Basic and Python can use mathematical model equations for simulation (Dysarz, 2018). Researchers have in the past used these softwares to simulate the performance of machines before full-scale development and, after that, only construct the most promising design. Osueke (2011) simulated operating parameters using visual Basic computer-aided software to determine and identify the performance characteristic of least threshing loss due to grain damage, incomplete threshing, and threshing efficiency. The software was designed to determine the effect of a range of varied machine and crop parameters on the performance of a cereal thresher and hence select the best set of parameters. In this study, Python was selected because it is free and open-source, object-oriented, simple and easy to use, has many libraries including Numpy, Scipy, and Sympy for manipulating mathematical and numerical expressions, constants, and multi-dimensional matrices (Hart *et al*., 2011). In this study, mathematical model equations with a set of assumptions concerning the operation of the common bean's thresher were coded. The execution of models represented by a computer program was meant to answer questions that were dynamic in nature through quantitative ways.

2.5 Optimization Techniques of Cereal Threshers

Some of the important common beans and machine variables include moisture content, bulk density, pegs` peripheral velocity, concave clearance, concave width and mass of the threshing cylinder (McDonald & Copeland, 2012). Variation of the mentioned variables results in different outputs of threshing efficiency, power requirement, throughput capacity, and grain damage. This, therefore, creates an optimization problem to be solved for efficient machine functioning. Several optimization techniques used by researchers include mathematical methods by use of calculus, linear, nonlinear, dynamic, geometric, separable, and quadratic programming (Rao, 2019). In addition, stochastic techniques are also used for optimization where the role of input parameters is highly uncertain by simulation methods, Markov processes, queuing, and renewal theory. Finally, statistical methods can also be used for solving optimization problems by the design of experiments, pattern recognition, regression, and discriminate analysis (Ryan, 2011).

Nalado (2015) defined optimization procedures as the study of problems in which one seeks to minimize (or maximize) a real function by choosing the values of integer variables from within an allowed set. Design of experiments, on the other hand, is a statistical approach that attempts to provide a predictive knowledge of a complex, multi-variable process with few trials. There are several tools that can be used for optimization which include: response surface methodology, artificial neural networks, Taguchi method and computer simulation programs (Datta & Mahapatra, 2010).

Response surface methodology (RSM) is a collection of statistical and mathematical methods that have an objective of optimizing a response surface influenced by various process parameters. RSM also quantifies the relationship between the controllable input parameters and the obtained response surfaces with the aim of optimizing the response variable; it is assumed that the independent variables are continuous and controllable by experiments with negligible errors. It is required to find a suitable approximation for the true functional relationship between independent variables and the response surface (Abich, 2018).

Artificial neural networks (ANNs) are a computer programs, which recognize patterns in a given collection of data and produce model for that data. ANN emulates brain in two ways: knowledge is acquired by the network through a learning process (trial and error); and interneuron connection strengths (i.e., synaptic weights), are used to store the knowledge (Agatonovic-Kustrin and Beresford, 2000). ANNs have been widely employed to solve real life problems related to classification, function approximation, data processing, and robotics. The training algorithm used to determine various parameters of ANN is one of the key factors that influence the performance of ANNs. However, low convergence speed is experienced when ANN is used (Yu *et al.*, 2015).

The Taguchi method was initially developed by Dr. Genichi Taguchi for improving the quality of goods manufactured (Park and Ha, 2005). According to Mostafa *et al*. (2013), Taguchi technique is an engineering methodology for obtaining product and process conditions which produce high-quality products with less development and cost of manufacturing.

Finally, model-based programs can be developed using existing programming languages to compute predicted values based on mathematical models from the first principles. This method is compatible with the threshing process since models can be developed to define the processes. The design of the package will involve; general design principles, structure and implementation as well as function of various modules (Osueke, 2011).

Anwer *et al*. (2021), optimized the performance of a longitudinal axial flow rice thresher using the Taguchi technique. The thresher structure and operating parameters were assessed and optimized with reference to threshing efficiency, required power, and productivity. The highest efficiency of 98% and the maximum productivity of 0.64 kg/s were obtained using the conical-shaped thresher under a 1500 rpm rotating speed and a feed rate of 1.4 kg/s, whereas the minimum required power of 5.45 kW was obtained using the conical thresher under a rotating speed of 1100 rpm and a feed rate of 0.8 kg/s. However, the study did not focus on grain damage as well as important machine parameters like concave clearance, width, and diameter. Singh and Vinay (2014) optimized machine parameters of Parvatiya Sugam motorized thresher using response surface methodology. The results, however, only indicated performance evaluation of the machine rather than the optimization criteria and outputs.

This study focussed on the optimization of common beans thresher using the Taguchi technique. The design of experiments can be conducted on a model or experimental system. Several designs of experiments have been used by researchers for optimization. Full factorial designs are used where the number of factors is few but with strong interaction. According to Wangete *et al.* (2016), the Taguchi method helps to choose the best variable combination factors for optimal operating conditions with the least number of analytical investigation and at a lower cost than the full factorial experiment. In the Taguchi experimental design, two factors that affect the output are identified. The control factors that can be managed easily and noise factors that are difficult or expensive to control such as ambient temperatures. A class of statistics known as signal to noise ratio is used to measure the effect of the factors on process performance and hence represents the ratio of sensitivity to variability. The higher the signal to noise ratio value the better the quality of the output. Therefore, Taguchi design of experiments maximizes signal to noise ratio to minimize the effect of random noise factors.

2.6 Criteria for Evaluating Threshing Performance

Performance evaluation is a scientific method of ascertaining the working conditions of the main components of a system with a view of establishing how the components contribute to the overall efficiency of the system (Peffers *et al.,*2007). From available literature on the various stationary mechanical threshers, the following performance criteria or parameters have been established for evaluating different threshing mechanisms. These include: threshing efficiency; grain loss or damage; grain output capacity and power requirement (El-Behery, 1995). These criteria are measured against the design variables namely; crop moisture content, concave length, crop feed rate, concave clearance, cylinder threshing speed, cylinder width and cylinder diameter. The definition of these variables is as follows (Sinha, 2009).

Threshing efficiency is the ratio of grain threshed (by weight) during initial threshing to the total expressed as a percent (or quantity of threshed grain in a sample to total grain in the sample expressed as percent). According to Singh *et al.* (2015), threshing efficiency is the ratio of mass of threshed grains received from all the outlets to total grain input per unit time expressed in percentage (%) (Singh *et al.*, 2015).

Total grain loss is the sum of threshing loss and grain damage loss whereas grain damage loss is the loss due to mechanical damage of grain as determined by visual examination and can be expressed as the ratio of broken, cracked, or chipped kernels, to the total expressed as percent. Nalado (2015) defined grain damage as the percentage of visually broken, chipped or cracked grain to the total grains threshed per unit time. It is a result of direct impact between the beaters of the threshing drum and the crop fed. A thresher separates grain from pod and stalk by applying pressure and impact force. The movement of the crop between stirring components of the threshing unit and improper clearance between the moving and stationery components causes damage to the grains (Ukatu, 2006).

Grain output capacity is the amount of grain threshed in an hour expressed in kg/hr also known as throughput capacity. It depends on mean rate of threshing, number of grains passing through the concave openings in one second per impact and dwell time of crop in the thresher (Ndirika, 2005). The kernels of the crop are bonded to the crop head by some forces which need to be overcome in order to separate the kernel from the head. This force is dependent upon the kind of crop, degree of ripeness of the crop and kernel moisture content and that it varies with size, form and structure of the plant tissue holding the kernels (Ndirika, 2006).

Power requirement is the kilowatt power required to thresh a given quantity of crop material. The power required to drive the threshing drum shaft is an important factor on the operational cost of the thresher. Variables that include crop moisture content, concave length, crop feed rate, concave clearance, cylinder threshing speed, cylinder width and cylinder diameter supposedly affect energy consumption (Vejasit & Salokhe, 2004).

Grain moisture content is the weight of moisture per unit weight of grain/straw expressed in percent. The moisture content of grain which is determined on wet basis gives the safe range of efficient threshing and grain damage. From various studies (Concave, 1969) it was found that moisture content influences threshability and kernel damage. It was also noted that straw moisture content has greater effect on threshing performance than grain moisture content (Lin, 1977). It was reported by (Osueke, 2011) that there is a range of moisture content for which the threshing efficiency, grain damage and output capacity can be affected. Beyond this range any increase in moisture content had no significant effect on threshing performance parameters.

Crop feed rate is the total material including grain, straw and chaff that passes through the threshing unit measured in kg/hr. Sudajan *et al.* (2002) reports on the effect of feed rate on the cleaning efficiency. An initial increase was observed in the cleaning efficiency with increasing feed rate until a maximum value of 96.5 % was obtained at 9.58kg/s. After this, there was a decrease in the cleaning efficiency with increasing feed rate. The behaviour of the cleaning efficiency against the feed rate may be due to increasing load intensity on the sieve. Multiple particles act as obstructions to the airflow (Sudajan *et al.*, 2002).

Concave clearance is the distance between the cylinder bar or spike tooth and the front concave bar measured in mm. Clearance between the threshing drum and the concave affects throughput capacity and grain damage. According to Špokas *et al.* (2008), when the clearance was increased at the beginning of the concave more grain was threshed at the concave end, they were not separated through the concave and were thrown on the straw walkers together with the straw. To minimize the grain damage and straw crumble when very dry cereals are harvested with combines, New Holland CSX 7080, increasing the clearance between the threshing drum and the concave from 10-10 mm to 12-12 mm had no significant influence on the grain damage (Špokas *et al.*, 2008).

Cylinder threshing speed is the peripheral speed of the cylinder measured in revolution per minute or m/s. An optimum speed is desirable for optimal performance of a thresher because excessive speed can cause the grain to crack while a low speed can give unthreshed head. Impact force is the primary threshing action for detachment of grain from the ear head. In all types of threshers, this impact force is controlled by the cylinder tip speed. The speed of the threshing drum influences the capacity and performance of a thresher (Gbabo *et al.*, 2013). Singh *et al.* (2015) developed and evaluated a multi-crop thresher and found that increase in the level of drum speed had significant effect on the threshing efficiency of the thresher.

Cylinder diameter is the diameter of the circle generated by the outermost point of the cylinder threshing element expressed in meters. Huynh *et al.* (1982) identified drum diameter as one of the parameters that influence grain separation from the stalks and passage of grains through the concave grate (Huynh *et al.*, 1982). Cylinder width is the length of the cylinder bar measured parallel to the cylinder axis expressed in meters. As reported by Chhabra (1975), the adequate drum length for an axial flow thresher was 203.2 cm at and any further reduction in the length caused separation losses. As the concave area was increased from $0.73m^2$ to $2.09m^2$ by using two concaves, it was noted that there was an improvement in separation efficiency (Dhiraj Kumar, 2003). Concave length is the distance from the front of the first bar to the rear of the last bar measured around the contour formed by the inner surface of the bars.

2.7 Source of Power for Operation of Threshers

Farm power for various agricultural operations can be broadly classified as: Tractive work such as seed bed preparation, cultivation, harvesting and transportation, and stationary work like silage cutting, feed grinding, threshing, winnowing and lifting of irrigation water. These operations are done by different sources of power, namely human, animal, oil engine, tractor, power tiller, electricity and renewable energy that includes biogas, solar and wind (Sahu *et al.*, 1980). Therefore, since threshing is classified under stationary work, the suitable power sources are fuel engine, tractor power take off and solar energy.

Oil engine are highly efficient devices for converting fuel into useful work. The efficiency of diesel engine varies between 32 and 38%, whereas that of the carburettor engine is in the range of 25 and 32% (Sirman *et al.*, 2000). In recent years, diesel engines and tractors have gained considerable popularity in agricultural operations. Small pumping sets within 3 to 10 hp range are very much in demand. Likewise, oil engines of low to medium speed developing about 14 to 20 hp are successfully used for flourmills and cotton gins. Diesel engines of the larger size are used on tractors. In the case of handling threshing operations in farm field, small diesel engines are the most suitable for powering common beans threshers.

Solar energy is a renewable primary source which is freely available and clean for useful stationary farm operation like threshing. Kenya receives solar energy of between 4 and 6 kWh/m^2/day. The country's annual average solar flux is about 5 kWh/m^2/day which is equivalent to 250 million tonnes of oil equivalent per day (Kiplagat *et al.*, 2011). Kenya has high insolation rates with an average of 5 peak sunshine hours, equivalent number of hours per day when solar irradiance averages 1000 W/m^2. The total amount of solar energy ranges from 700 kWh in mountainous regions to 2650 kWh in arid and semi-arid regions per year. Most parts of the country lie in the range of 1750–1900 kWh range. However, only an insignificant amount out of this vast resource is hitherto harnessed.

Diverse application of solar energy includes solar thermal for heating and drying and solar photovoltaic (PV) for lighting, water pumping, crop drying, refrigeration and telecommunications. In Kenya, there has been a deliberate effort to electrify the country in urban and rural areas with a figure of 63.81% access to electricity in 2018 (Mabea *et al.*, 2018). However, due to weak grids and loading profiles, blackouts are experienced in most parts of the country. It's in this regard that solar energy is proposed to be used for the stationary common bean thresher. Various solar energy storage devices are available in the market which include; liquid lead acid, maintenance free lead acid and lithium-ion batteries. The best batteries were selected based on the life cycle and the power load for integration.

2.8 Summary of the Literature Review and Research Gaps

From the preceding literature review, it can be noted that not much has been done on the modelling and optimization of design parameters in relation to performance of portable common bean threshers. Most of the models are for combine systems which have different crop model from stationary mechanical threshers. Also, most of the models have not been implemented to rate their success, some could not give clear explanation on how some of the physical parameters are derived. Most of the mathematical models that have been developed did not include moisture content parameter in their formulation, except the threshing process model developed by Enaburekhan (1994) which included moisture content parameter. His moisture content parameter was proposed from intuitive reasoning. It is therefore necessary to develop performance simulation models for describing and predicting the performance of the threshing and separation processes for stationary common bean.

To understand the effect of machine and crop parameters on performance of common beans thresher, simulation is necessary using a mathematical model. Modelling and simulation are the use of physical, scientific, or rational representation of a system or process to generate performance data (Law *et al*., 2000). Simulation can be achieved by developing prediction model equations which are validated using experimental measured data. Softwares like Visual Basic and Python can use mathematical model equations for simulation (Dysarz, 2018). Researchers have in the past used these softwares to simulate the performance of machines before full-scale development and, after that, only construct the most promising design. Osueke (2011) simulated operating parameters using visual Basic computer-aided software to determine and identify the performance characteristic of least threshing loss due to grain damage, incomplete threshing, and threshing efficiency. The software was designed to determine the effect of a range of varied machine and crop parameters on the performance of a cereal thresher and hence select the best set of parameters. In this study, Python was selected because it is free and open-source, object-oriented, simple and easy to use, has many libraries including Numpy, Scipy, and Sympy for manipulating mathematical and numerical expressions, constants, and multi-dimensional matrices (Hart *et al*., 2011).

The design and development of cereal grain threshers is not entirely a grey area. Various cereal stationary threshers exist for different crops like sorghum, rice, cashew nuts, and millet. However, there is scanty information on common beans thresher. Reported findings have mainly been based on experimental data and few theoretical modelling of the threshing unit. Desta and Mishra (1990) developed and evaluated the performance of an experimental sorghum thresher. Their results focused mainly on the optimum operating speeds and average threshing efficiency was 98% at 400 revolutions per minute (rpm). Singh *et al*. (2015) developed a multi-crop thresher and evaluated the effect of cylinder speed on threshing efficiency. The results indicated that an increase in the level of drum speed had a significant effect on the threshing efficiency of the thresher.

The impact of maize sheller in increasing production and making work easier has been felt in Kenya. The majority of farmers use maize sheller for shelling maize because it is readily available in the market produced by the informal sector. This could be one of the reasons why maize is the first staple food crop in Kenya. The same principle of mechanization of threshing activities for common beans could be a game-changer in attracting many Kenyans to grow beans to meet the consumption demand as well create employment for the machine producers. As reported earlier, there have been attempts to design and fabricate common beans thresher by Kenya Agricultural and Livestock Research Organization (KALRO) apart from the imported ones from China and America. However, grain damage caused by impacts of the moving parts of crop threshing units and incorrect clearances between the stationary and moving parts of the units are some of the concerns to bean farmers and consumers (Fu *et al.,* 2018). Optimization of key input factors is hence necessary for the design of an improved machine system.

Some of the important common beans and machine variables include moisture content, bulk density, peripheral velocity of the pegs, concave clearance, concave width and mass of the threshing cylinder (McDonald & Copeland, 2012). Variation of the mentioned variables results in different outputs of threshing efficiency, power requirement, throughput capacity, and grain damage. This, therefore, creates an optimization problem to be solved for efficient machine functioning. Several optimization techniques used by researchers include mathematical methods by use of calculus, linear, nonlinear, dynamic, geometric, separable, and quadratic programming (Rao, 2019). In addition, stochastic techniques are also used for optimization where the role of input parameters is highly uncertain by simulation methods, Markov processes, queuing, and renewal theory. Finally, statistical methods can also be used for solving optimization problems by the design of experiments, pattern recognition, regression, and discriminate analysis (Ryan, 2011).

Several designs of experiments have been used by researchers for optimization. Full factorial designs are used where the number of factors is few but with strong interaction. According to Wangete *et al.* (2016), the Taguchi method helps to choose the best variable combination factors for optimal operating conditions with the least number of analytical investigation and at a lower cost than the full factorial experiment. In the Taguchi experimental design, two factors that affect the output are identified. The control factors that can be managed easily and noise factors that are difficult or expensive to control such as ambient temperatures. A class of statistics known as signal to noise ratio is used to measure the effect of the factors on process performance and hence represents the ratio of sensitivity to variability. The higher the signal to noise ratio value the better the quality of the output. Therefore, Taguchi design of experiments maximizes signal to noise ratio to minimize the effect of random noise factors.

A number of gaps were identified in literature review, these include inadequate models to describe the effect of common beans characteristics (e.g., bulk density, moisture content, grain straw ratio, grain geometry and length of bean straws) on the performance of bean threshers. In addition, the relationship between machine and operational factors (e.g., length of the concave, concave clearance, concave width, cylinder diameter feed rate and pegs peripheral speed) on performance of the system is not well explained by existing models. Furthermore, existing dry bean threshers have high mechanical grain damage with low threshing efficiency because most of the designs are experimental. Finally, existing bean threshers require improvement by considering all the variables affecting the performance of the machine.

2.9 Conceptual Framework

The structure for the study based on literature is illustrated diagrammatically showing relationship between independent and dependent variables in the conceptual frame work shown in Figure 2.6.

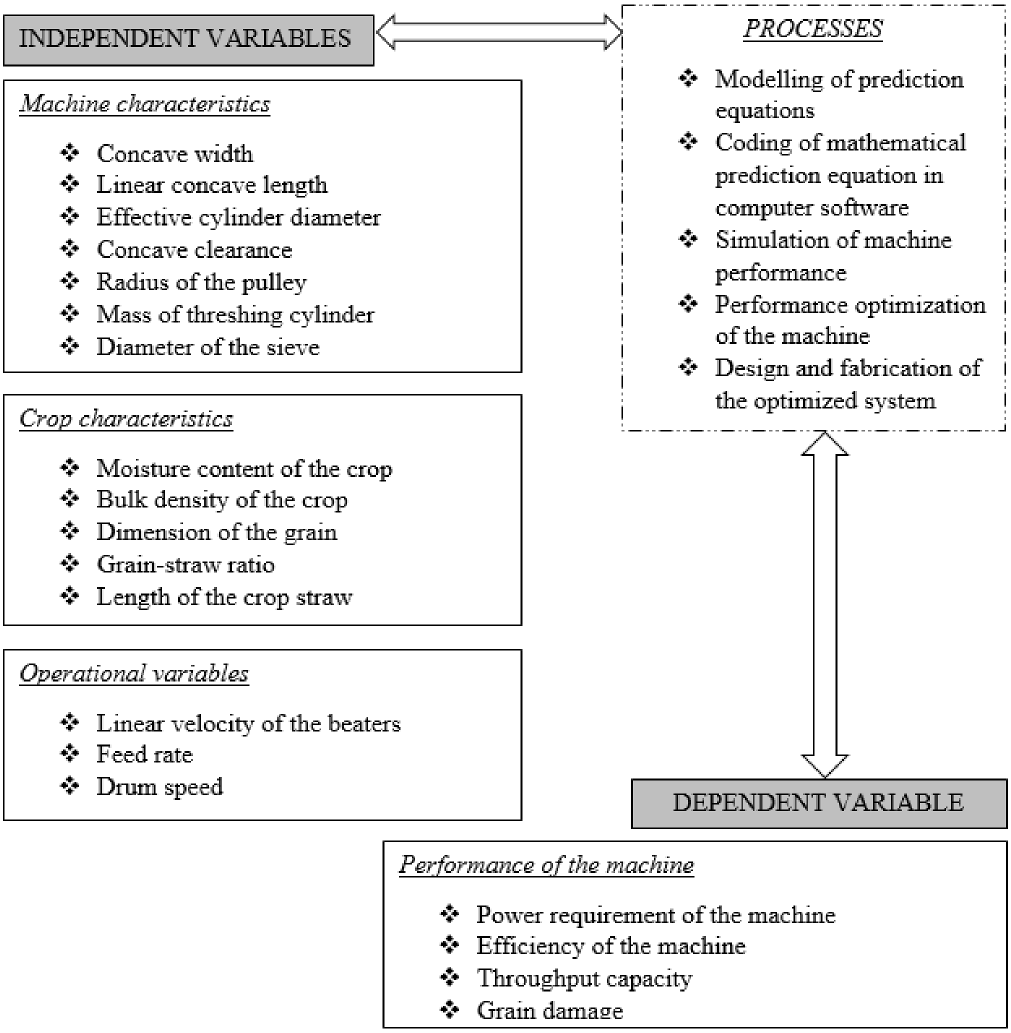


Figure 2.6: Conceptual framework.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Simulating Design Parameters and Evaluating the Performance of the Common Beans Thresher

Simulation was done by setting up a computer-based model of bean thresher and then performing experiments on it. It was a stepwise process of developing mathematical prediction equations, coding in python software and simulating scenarios based on input variables. The schematic model of the common bean threshing unit that was modelled and simulated is indicated in Figure 3.1. The modelled threshing unit consisted of a cylinder drum with the pegs attached in a spiral configuration, concave that forms part of the sieve, and concave clearance. The key performance models developed that described the threshing unit were; power requirement, threshing efficiency, threshing loss, grain damage, and output capacity.

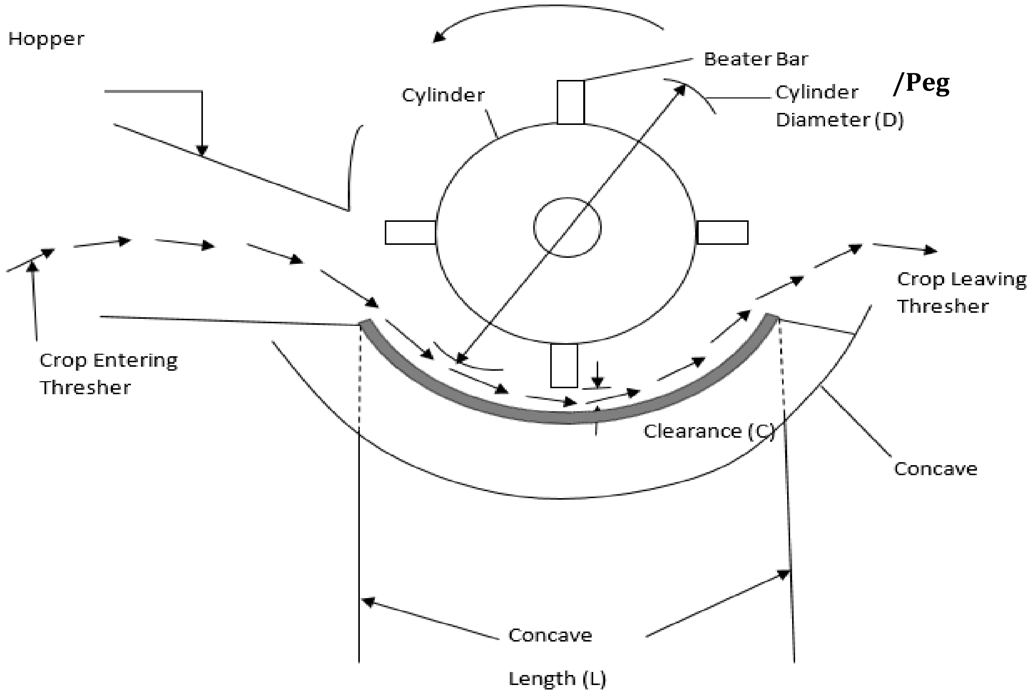


Figure 3.1: Schematic of cylinder-concave of spike tooth threshing mechanism.

Adopted from: Ndirika (2005)

3.1.1 Mathematical models relating design parameters and performance of thresher

3.1.1.1 A model for power requirement

The model for power requirement was developed by combination of dimensional analysis using the concept of Buckingham’s` Pi theorem and mechanic theory. It was a sum of power required to detach the grains from the pods, power required to overcome friction and the power required to turn the loaded cylinder. The power required to detach the grains from the pods, Pi was determined by first defining the energy required to detach the grain from the panicle, *E*.

This energy E, was determined using dimensional analysis by considering related factors of influence. The variables of importance were assumed to be; crop velocity V_c, crop bulk density (wet basis) ρ_w, federate *F*, concave clearance *C*, concave length L_c and cylinder diameter *D*. However, since concave clearance, concave length and cylinder diameter are usually fixed during threshing operation, these three variables were assumed constant. Therefore, the energy required to detach grain from the panicle was given as in Equation 3.1:

$$E = f(V_c, \rho_w, F_r) \qquad (3.1)$$

Using [M], [L], [T] system of dimensions and applying the Buckingham`s pi theorem to identify the dimensionless groups to be formed, the energy required to detach the grains from the panicles in Equation 3.1 was transformed into Equation 3.2. In this equation, K_s is the energy coefficient.

$$E = K_s \left(\frac{V_b^{1/2} F_r^{3/2}}{\rho_w^{1/2}} \right) \qquad (3.2)$$

The power required to detach the grains from the panicles, Pi was then expressed as shown in Equation 3.3:

$$P_i = E/t_d \tag{3.3}$$

But for a given concave length (L_c) and crop velocity (V_c), the dwell time (t_d) of the crop in the thresher was expressed as stated in Equation 3.4, in which L_c is concave length (m), V_c is crop velocity (m/s) and t_d is dwell time (s).

$$t_d = \frac{L_c}{V_c} \tag{3.4}$$

The average velocity (V_c) of the crop in the threshing zone was then estimated by representing the peripheral velocity of the cylinder or beater (V_b), linear velocity of the feeder (V_f) and the velocity of the crop in the threshing zone in a velocity diagram. It was formerly resolved for velocities by Pythagoras theorem to obtain the crop velocity (V_c). Hence an average velocity was defined by Equation 3.5. In this equation, V_f is linear velocity of the feeder (m/s), V_b is peripheral velocity of the cylinder or beater (m/s) and V_c is the average velocity (V_c) of the crop in the threshing zone (m/s).

$$V_c = \left(V_f^2 + V_b^2\right)^{1/2} \tag{3.5}$$

Since the feeding was manual, V_f was small compared to V_b, and as such it was assumed to be negligible. Considering a slip factor for the beater bar as K_b, the crop mixture was assumed to haul around the concave at the velocity given in Equation 3.6.

$$V_c = K_b V_b \tag{3.6}$$

Substituting the value of V_c from Equation 3.6 into Equation 3.4 resulted to Equation 3.7

$$t_d = \frac{1}{K_b}\left(\frac{L_c}{V_b}\right) \qquad (3.7)$$

Substituting the value of dwell time in Equation 3.7 and the energy required to detach the grains from the panicles in Equation 3.2 in Equation (3.3) resulted into Equation 3.8 that predicts the power required to detach the grain from the panicle for a given crop.

$$P_i = K_b\left(\frac{{V_b}^{1/2}{F_r}^{3/2}V_c}{{\rho_w}^{1/2}L_c}\right) \qquad (3.8)$$

In determining the power required to overcome friction, the pressure of the crop stream on the concave surface was assumed to be uniformly distributed over the entire length and width of the concave. Therefore, by dimensional analysis, the force (F) required to move the crop material around the concave was related to the mass feed rate and velocity as indicated in Equation 3.9: In this equation F is frictional force to be overcome before the crop material move around the concave and μ is the dimensional constant referred to as coefficient of motion resistance of crop stream on the concave.

$$F = \mu F_r V_c \qquad (3.9)$$

Substituting the value of V_c from equation 3.6 into equation 3.9 resulted into Equation 3.10 which was the force required to overcome friction.

$$F = \mu k_b F_r V_b = K_a\, F_r.V_b \qquad (3.10)$$

Therefore, the power required to overcome the friction was given by Equation 3.11:

$$P_f = F.V_c \qquad (3.11)$$

Substituting the value of V_c from Equation 3.6 into Equation 3.11 resulted to Equation 3.12:

$$P_f = K_b.V_b.F \qquad (3.12)$$

Substituting the value of F from Equation 3.10 into Equation 3.12 gives Equation 3.13:

$$P_f = K_a.K_b.F_r.V_b^2 \qquad (3.13)$$

Replacing $K_a.K_b$ with K_f (frictional constant) then Equation 3.13 was simplified to Equation 3.14 which predicted the power required to overcome frictional force.

$$P_f = K_f F_r V_b^2 \qquad (3.14)$$

The power required to turn the unloaded cylinder was based on the rotational speed without load and the torque required to run the cylinder without load. The force required to turn the threshing cylinder without load was expressed by Equation 3.15. In this equation, M_c is mass of the threshing cylinder (kg), a` is sum of acceleration due to gravitational force (g') and the centrifugal acceleration of the cylinder.

$$F' = M_c a' \qquad (3.15)$$

The centrifugal acceleration for the cylinder was also expressed as in Equation 3.16, where V_b (m/s) is the velocity of the cylinder without load and D (m) is the effective diameter of the cylinder.

$$a' = g' + (2V_b^2/D) \qquad (3.16)$$

Substituting the value of a` in Equation 3.16 into Equation 3.15 resulted into Equation 3.17:

$$F' = M_c\left(g' + 2V_b^2/D\right) \qquad (3.17)$$

The torque T' required to turn the threshing cylinder without load was expressed as in Equation 3.18 according to Ndirika (2006). In this Equation, Y is the radius of the driven pulley of the cylinder (m)

$$T = F^{/}Y \tag{3.18}$$

Substituting the value of $F^{/}$ from Equation 3.17 into Equation 3.18 yielded into Equation 3.19:

$$T^{/} = M_c Y\left(g^{/} + 2V_b^2/D\right) \tag{3.19}$$

Power P_r, required to run the cylinder without load was expressed as in Equation 3.20 according to Ndirika (1988) in which N is the cylinder rotational speed without load.

$$P_r = N.T` \tag{3.20}$$

Substituting the value of $T^{/}$ from Equation 3.19 into Equation 3.20 gives Equation 3.21:

$$P_r = M_c YN\left(g^{/} + 2V_b^2/D\right) \tag{3.21}$$

Expressing Equation 3.21 in the units of power resulted into Equation 3.22:

$$P_r = 2\pi M_c YN\left(g^{/} + 2V_b^2/D\right)/60 \tag{3.22}$$

Therefore, the prediction model for total power (watts) required for threshing operation was expressed as in Equation 3.23:

$$P = P_i + P_f + P_r \tag{3.23}$$

Substituting the values of Pi, P_f and P_r into Equation 3.23 resulted in Equation 3.24 which is useful in simulating the total power required for threshing operation.

$$P_T = K_a\left(\frac{V_p^{\frac{1}{2}}Q_r^{\frac{3}{2}}V_p}{\rho_w^{\frac{1}{2}}L_c}\right) + K_bQ_rV_p^2 + \frac{2\pi M_cYN(g/+2V_p/D)}{60} \qquad (3.24)$$

3.1.1.2 Modelling threshing process

The exponential probability density function as used by Ndirika, (1997), Miu, (2002) and Huynh *et al.*, (2019) was considered for describing and predicting the process performance and various variables influencing threshability. The process was described as a probability of equal likely events that assumed that any bean grains had an equal chance of being threshed at any time and had an equal chance of reaching the concave surface at a given position. The exponential probability density function was defined as in Equation 3.25. In this equation, t is occurrence time of random events (threshing of grain) in seconds, and λ was mean rate of threshing (kg/s).

$$f(t) = \lambda e^{-\lambda t} \qquad (3.25)$$

Integrating Equation 3.25 with respect to time t, at time interval of ($0 < t < t_d$) to obtain fraction of the grain threshed within the interval, T_e resulted into Equation 3.26.

$$T_e = 1 - e^{-\lambda_1 td} \qquad (3.26)$$

Equation 3.26 described the threshing efficiency parameter which is depended on the rate of threshing and the dwell time of threshed grain in the threshing zone. But the formula for dwell time was given by Equation 3.27 (Miu and Kutzbach, 2008; Huynh *et al.*, 2019 and Ndirika, 1997.

$$t_d = {}^{L_c}\!/_{V_g} = {}^{L_c}\!/_{\left({}^{2}\!/_{3}\,V_b\right)} = {}^{3L_c}\!/_{2V_b} \qquad (3.27)$$

The Threshing frequency or the mean rate of threshing, λ_1 was determined by use of dimensional analysis. The important variables that influence λ_1 were assumed to be cylinder velocity V_b, crop bulk density ρ_w, feed rate F_r, and cylinder diameter, D. Hence, the mean threshing parameter was given by Equation 3.28:

$$\lambda_1 = f(V_b, \rho_w, F_r, D) \tag{3.28}$$

Using [M], [L], [T] system of dimension and applying the Buckingham's pi theorem to identify the dimensionless group formed, Equation 3.29 was developed.

$$\lambda_1 = K_T \left(\frac{F_r}{D^3 \rho_w} \right) \tag{3.29}$$

Substituting t_d and λ_1 from Equation 3.27 and 3.29 respectively into Equation 3.26 yields Equation 3.30 that predicted threshing efficiency of common beans thresher.

$$T_e = 1 - e^{\left[\frac{1.4 \times K_T \times \rho_d \times w \times D \times V_p^2 L_c}{(1-\beta) Q_r} \right]} \tag{3.30}$$

In Equation 3.30, T_e is the threshing efficiency of the thresher, K_t is the threshing constant, ρ_d is the dry bulk density of common beans, w is the concave length, and β is the moisture content of common beans. Threshing loss T_L was defined by Equation 3.31, the fraction of unthreshed common beans expressed in percentage.

$$T_L = 1 - T_e \tag{3.31}$$

Substituting T_e in Equation 3.30 into Equation 3.31 resulted into Equation 3.32, which was used to predict threshing loss.

$$T_L = -e^{\left[\frac{1.4\times K_T \times \rho_d w \times D \times V_p^2 L_c}{(1-\beta) Q_r}\right]} \qquad (3.32)$$

3.1.1.3 A model for predicting grain mechanical damage

Damage parameter, λ_d which was the mean rate of damaged grain was important in the development of the damage model. It was determined by the use of dimensional analysis. The variables of importance influencing damage parameters were assumed to be cylinder velocity, V_b, crop bulk density, ρ_w, feed rate, F_r, cylinder diameter, D and minimum velocity to cause grain damage V_d. Therefore, Equation 3.33 described the damage parameter, where V_b is cylinder Velocity (m/s), ρ_w is crop bulk density (g/m^3), F_r is feed rate (g/s), D is cylinder diameter (m) and V_d is minimum velocity to cause grain damage (m/s).

$$\lambda_d = f(V_b, \rho_w, F_r, D, V_d) \qquad (3.33)$$

Using [M], [L], [T] system of dimension and applying Buckingham's pi theorem to identify the dimensionless groups to be formed, Equation 3.34 was developed.

$$\lambda_d = K_d \left(\left({D^2 V_b \rho_w}/{F_r} \right)^{\frac{1}{2}}, {V_b}/{V_d}, \left({V_d^3 \rho_w}/{F_r} \right)^{\frac{1}{2}} \right) \qquad (3.34)$$

The integral of exponential probability density function as in Equation 3.35 was used to develop expression for the fraction of grain damage within the time interval $0 < t < t_d``$ in the threshing zone. From this interval it implied that the fraction threshed within the interval, T_g was given by Equation 3.35:

$$T_g = \int_0^{t_d^{``}} \lambda_d e^{-\lambda_d t} dt \tag{3.35}$$

The damaged fraction, D_f was represented in Equation 3.36

$$D_f = 1 - \int_0^{t_d``} \lambda_d e^{-\lambda_d t} dt \qquad (3.36)$$

Fraction of damaged common beans was further defined based on integral exponential probability density function within dwell time in the threshing unit. Equation 3.37 was used to express the fraction of the damaged common beans on impact by the pegs (Osueke, 2011; Gregory, 1988 and Fu *et al.*, 1982). In this equation, D_b is the fraction of damaged common beans grains in the equation, and K_d is the damaged constant.

$$D_b = e\left[\frac{-0.5K_d \rho_d D V_p w L_c}{(1-\beta)Q_r}\right] \qquad (3.37)$$

3.1.1.4 Throughput capacity model

The thresher output capacity model was developed by dimensional analysis, using the concept of Buckingham's pi theory. The variables of importance were assumed to be feed rate F_r, grain-straw ratio (Z) and separation efficiency (S_e). Separation efficiency was the fraction of threshed grain that was recovered through the concave opening by the concave configuration. Therefore, output capacity of a thresher was defined by Equation 3.38:

$$C_T = f(F_r, Z, S_e) \qquad (3.38)$$

Using the [M], [L], [T] system of dimension and applying Buckingham’s pi theorem to identify the dimensionless groups to be formed, Equation 3.39 was developed in which K_m is the yield factor.

$$C_T = K_m F_r Z S_e \qquad (3.39)$$

The dependent events that were considered in the modelling of separation efficiency were: detachment of the grain from the crop head, migration of the grains through the crop stream and passage of grain through opening. Huynh *et al*., (1982) and Ndirika, (2006) predicted separation efficiency as shown in Equation 3.40. This equation predicted the fraction of threshed grains that was recovered through the concave opening.

$$S_e = 1 - \left\{ \frac{\left[\lambda_1 \lambda_3 (\lambda_3 - \lambda_1) e^{-\lambda_2 t_d} + \lambda_2 \lambda_1 (\lambda_1 - \lambda_2) e^{-\lambda_3 t_d} + \lambda_2 \lambda_3 (\lambda_2 - \lambda_3) e^{-\lambda_1 t_d} \right]}{\left[(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)(\lambda_3 - \lambda_1) \right]} \right\} \tag{3.40}$$

The Threshing frequency or the mean rate of threshing, λ_1 was determined by the use of dimensional analysis. The important variables that influenced λ_1 were assumed to be cylinder velocity V_b**,** crop bulk density ρ_w, feed rate F_r, and cylinder diameter, D. Equation 3.41 shows threshing frequency predicting equation that was developed. In this equation, K_T is threshing constant, V_b is peripheral velocity of beaters, δ_d is crop bulk density (dry basis), D is cylinder diameter, β is moisture content of wet crop and Fr is feed rate.

$$\lambda_1 = K_T \left(\frac{V_b^2 \delta_d D}{(1-\beta) F_r} \right) \tag{3.41}$$

The mean rate of migration or separation for grain through the crop stream thickness was modelled based on the application of Newton's second law of motion for a body under uniform acceleration starting from rest. It was assumed that the crop motion resistance force was constant and proportional to the force acting on the grain. The grain migration parameter was modelled and expressed as shown in Equation 3.42 (Ndirika, 2006), where *Kn* is the mean time coefficient and g^1 is acceleration due to gravitational force in the vertical direction.

$$\lambda_2 = \frac{1}{K_n} \left[\frac{\left[g' + {}^{2V_b^2}/_{D} \right]}{\left[{}^{(1-\beta)F_r}/_{\rho_d V_b} \right]^{\frac{1}{2}}} \right]^{\frac{1}{2}} \tag{3.42}$$

The assumptions made in determining the rate of grain passage through concave opening were that the grain slides through the crop stream with constant velocity, V_g across the concave surface. In addition, the passage of grain through a given concave opening formed by the rods and bars is only possible if the projection of the grain on the concave surface is within the concave opening and if the grain fails to pass through the concave opening it will move to the next concave opening at a constant speed (V_g). The probability of grain passage through the concave opening was determined using the relation by Huynh *et al*. (1982) and Ndirika (2006) as shown in Equation 3.43:

$$P^{/} = \frac{(a_1 - a_2 - d)(b_1 - b_2 - d_1)}{a_1 b_1} \tag{3.43}$$

In Equation 3.43, a_1 is centre line distance between rods (m), b_1 is centre line distance between bars (m), a_2 is rod diameter (m), b_2 is width of the bar (m), d_1 is average size of the grain which is considered spherical (m) and $P^{/}$ is probability of grain passage through the concave opening. The concave separation parameter was modelled into Equation 3.44.

$$\lambda_3 = \left(\frac{2V_g}{3b_1}\right)\frac{(a_1 - a_2 - d_1)(b_1 - b_2 - d_1)}{a_1 b_1} \tag{3.44}$$

Substituting separation efficiency in Equation 3.40 into Equation 3.39 resulted into Equation 3.45 (Ndirika, 2006; Gregory, 1988; Osueke, 2011), where C_T is the output capacity of the thresher, K_m is the yield factor, Z is the grain straw ratio, λ_1 is the mean rate of threshing, λ_2 is the grain migration parameter, λ_3 is concave separation parameter, and t_d is the dwell time in the threshing zone.

$$C_T = K_m Q_r Z\{1 - \left\{\frac{[\lambda_1\lambda_3(\lambda_3 - \lambda_1)e^{-\lambda_2 t_d} + \lambda_2\lambda_1(\lambda_1 - \lambda_2)e^{-\lambda_3 t_d} + \lambda_2\lambda_3(\lambda_2 - \lambda_3)e^{-\lambda_1 t_d}]}{[(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)(\lambda_3 - \lambda_1)]}\right\}\} \tag{3.45}$$

3.1.2 Simulating design parameters and evaluating performance of the thresher

In developing a simulation model, the best framework and language was chosen among visual basic dot net, web-based simulation model (Js), MATLAB, R, C, and python among many others. Python was selected because it is free and open source, object oriented, simple and easy to use, had many libraries including numpy, scipy and sympy for manipulating mathematical and numerical expressions, constants and multi-D matrices.

Python software was downloaded in components of Integrated Development Environment, Python v3.8 and PyCharm Professional Edition. The steps for installation were followed carefully and then an editor was opened. The program was designed in two versions, the first one had ten functions to return different components of the model in each function. It also was able to print out the equations used to model. Version two had only one main function that returned the values of all the outputs. The program began by displaying the current EAT time using the date and time built in module in the python 3.8.5 shell. The programme code used for simulation is shown in Plate A5 in the appendices.

The user was requested to enter all the input parameters shown in Table 3.1-3.3. This was followed by a series of arithmetic manipulations. After the inputs had been stored in the program, the code calculated the different output components as follows, dwell time, power to overcome friction, power to detach the grains, power to turn unloaded cylinder, total power, threshing loss and threshing efficiency and grain damage. Crop and machine parameters were entered individually and then simulated to view performance results. Parameters in Tables 3.1 and 3.3 were kept constant, while those in Table 3.2 were varied to ascertain their effect on the thresher performance. The choice of variables was based on the assumption of common bean crop and machine parameters that affect the performance of the bean thresher. In addition, past researchers have described feed rate, peg`s peripheral speed, concave clearance and length as some of key factors affecting performance of threshers (Ndirika, 1997).

Table 3.1: Fixed crop and machine input parameters into the model

Parameter	Values
Radius of the driven pulley, Y	0.045 m
Mass of threshing cylinder, M_c	5 kg
Center line distance between adjacent concave rods, a_1	0.04 m
Concave rod diameter, a_2	0.0018 m
Center line distance between adjacent concave bar, b_1	0.06 m
Width of concave bars, b_2	0.0085 m
Grain straw ratio, Z	0.9
Spherical size of common beans	0.016 m

Table 3.2: Crop and machine variables used for simulation

Variable	Variations					
Moisture content of common beans, β (%)	15	17.5	20	22.5	25	
Feed rate, Q_r (kgs^{-1})	0.01	0.02	0.03	0.04	0.05	
Peripheral velocity of the pegs, V_p (ms^{-1})	2	4	6	8	10	12
Concave clearance, c (m)	0.018	0.02	0.022	0.024	0.028	
Concave length, L_c (m)	0.25	0.5	0.75	1		

Table 3.2: Constants used in the applicable mathematical models

Constants	Values	Source
Acceleration due gravity, g`	9.8	Muna *et al.,* (2016)
Slippage factor, K_a	0.35	Desta and Mishra (1990)
Threshing constant, K_T	0.002	Huynh *et al.*, (1982) & Osueke,

		(2011)
Damage constant, K_d	8×10^{-3}	Ndirika, (1997) & Wagami, (1979)
Yield factor, K_m	0.7	Long et al., (1967) & Ndirika, (1993)

For easier simulation, a web-based interface for input variables was designed (Figure 3.2). The interface was portable (can be used on any device) and one does not need to install any python dependencies to use. However, it was necessary to set up the server, database and domain on Heroku Cloud Platform. The user had to input all the required variables before simulation to get outputs. To refresh, it had a clear button.

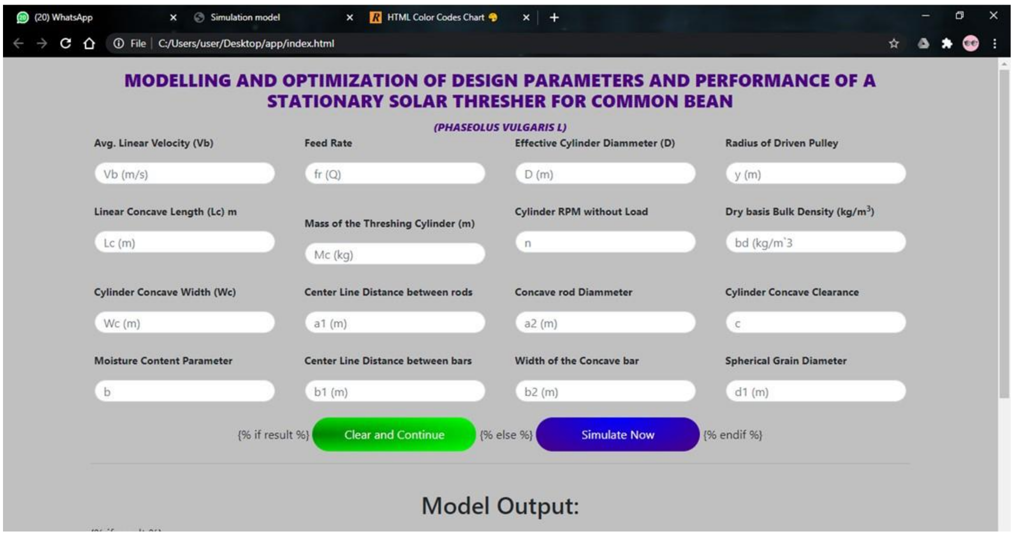
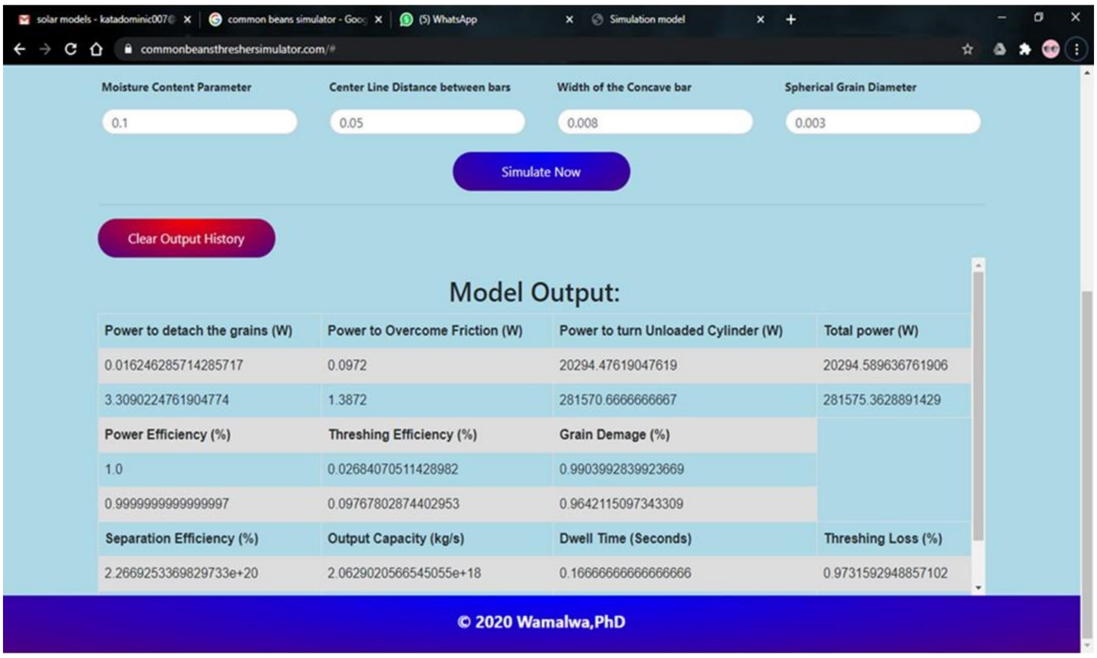


Figure 3.2: Computer interface for input simulation variables.

The computer interface for model output is shown in Figure 3.3. The results of the output were based on the coded mathematical prediction equation. The input fields were modified in a way to allow individual input to be modified independently during debugging.



Moisture Content Parameter
0.1

Center Line Distance between bars
0.05

Width of the Concave bar
0.008

Spherical Grain Diameter
0.003

Model Output:

Power to detach the grains (W)	Power to Overcome Friction (W)	Power to turn Unloaded Cylinder (W)	Total power (W)
0.016246285714285717	0.0972	20294.47619047619	20294.589636761906
3.3090224761904774	1.3872	281570.6666666667	281575.3628891429
Power Efficiency (%)	**Threshing Efficiency (%)**	**Grain Demage (%)**	
1.0	0.02684070511428982	0.9903992839923669	
0.9999999999999997	0.09767802874402953	0.9642115097343309	
Separation Efficiency (%)	**Output Capacity (kg/s)**	**Dwell Time (Seconds)**	**Threshing Loss (%)**
2.2669253369829733e+20	2.0629020566545055e+18	0.16666666666666666	0.9731592948857102

Figure 3.3: Computer interface for model output.

3.1.2.1 Model testing and validation

Figure 3.4 shows threshing unit of the developed common beans thresher used for validation. The developed prototype was modified from the existing threshers e.g., millet, sorghum and maize shellers (Abich, 2018; Ndirika, 1997). However, the following factors were considered in the design and modification of the common bean thresher prototype:

i. The length of unthreshed bean straws was used to determine the drum diameter. The correct diameter enhances smooth flow of material within the threshing unit by avoiding complete winding of straws around the cylinder drum.

ii. Peg`s peripheral speed rather than angular speed was used as a parameter due to the fact that the rubbing and impact-force required to thresh the grain of the common beans from the pods depends on the peripheral speed.

iii. The total weight and size of the machine were considered for easy transportation.

iv. The safe operating speeds was considered to avoid excess vibrations and high grain mechanical damage based on literature.

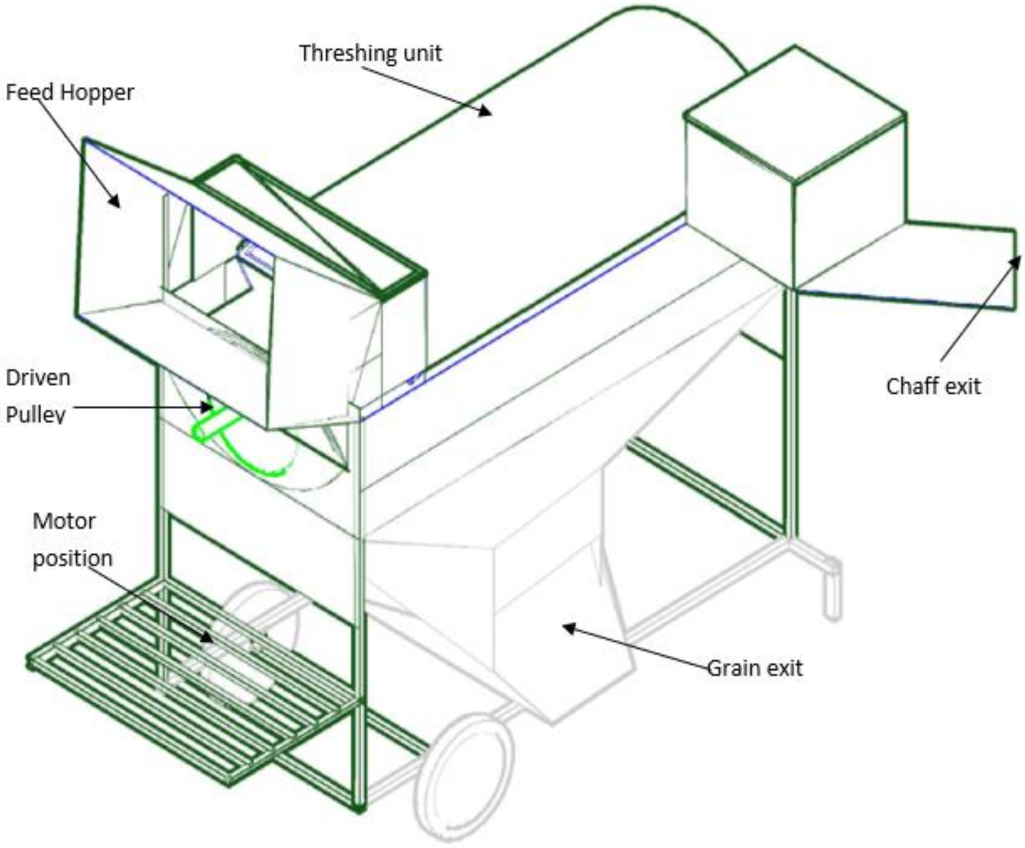


Figure 3.4: Schematic diagram for common beans thresher prototype.

The threshing unit consisted of a peg tooth threshing drum and perforated concave. The threshing drum was made of galvanized cylindrical metal pipe 1000 mm long through which a 25.4 mm shaft passed. Pegs were bolted in a staggered helical manner on the drum. At the end of the drum shaft a double groove V belt pulley made of cast iron was mounted on the shaft driven by a three phase 2.20 kW electric motor. The concave was 260 mm wide and 1000 mm long. A concave clearance of 22 mm based on the bean grain size was used in the design of the thresher. The support frame was fabricated from iron hollow section 39 mm by 25 mm. Its overall dimension was 1200 mm long, 260 mm wide and 1100 mm high. The feeding hopper was trapezoidal type made from mild steel sheet gauge 18 and tilted to feed the common beans by gravity flow. The height of hopper from the ground level was 1540 mm.

3.1.2.2 Design Analysis

The design analysis was carried out to evaluate the necessary design parameters, strength and size of materials for consideration in the selection of various machine parts. This was done to avoid failure by yielding and fatigue during the operation of the machine. Threshing drum diameter was required to determine the capacity of common bean threshing machine. This was determined using standard equation for calculating volume of a cylinder. Power transmission system was achieved by the use of pulley. Drum pulley diameter was based on maximum drum angular speed N determined by Equation 3.45 according to Adekanye (2016), in which V is the peripheral drum speed (m/s) and D_p is the drum diameter (m).

$$N = \frac{60 \times V}{3.14 \times D_p} \tag{3.45}$$

The drum shaft pulley diameter was established using Equation 3.46. In this equation, N1 is speed in rpm of prime mover pulley (m/s), N_2 is Speed in rpm of pulley of drum (m/s), d_1 is diameter of prime mover pulley (m) and d_2 is diameter of pulley on drum (m).

$$\frac{N_1}{N_2} = \frac{d_2}{d_1} \tag{3.46}$$

The power requirement was a sum of power required to overcome friction, the power required to detach the grains from the pods, blower power requirement and the power required to turn the unloaded cylinder. Therefore Equation 3.47 was used to predict the total power required for threshing common beans (Wamalwa *et al*., 2021; Osueke 2011; Ndirika, 1997). In this equation, P_T is total power required for threshing, K_a is slippage factor for cylinder pegs, V_p is the peripheral velocity of the pegs, Q_r is feed rate of common beans, ρ_w is bulk density of common beans (wet basis), L_c is concave length, K_b is a dimensional constant relating to motion resistance of the material, M_c is mass of the cylinder, Y is the radius of the driven pulley, N is cylinder RPM without load and *g*` is the acceleration due to gravity and *D* is the effective diameter of the cylinder.

$$P_T = K_a \left(\frac{V_p^{\frac{1}{2}} Q_r^{\frac{3}{2}} V_p}{\rho_w^{\frac{1}{2}} L_c} \right) + K_b Q_r V_p^2 + \frac{2\pi M_c Y N(g^{/} + 2V_p/D)}{60} \qquad (3.47)$$

The length of belt between prime mover and drum pulleys at nominal pitch length (L) was obtained using Equation 3.48, where L is Length of belt connecting the pulleys (m), d_p is diameter of prime mover pulley (m), D_p is diameter of drum shaft pulley (m) and C_p is distance between the centres of prime mover and drum pulley (m)

$$L = \frac{\pi}{2}\left(D_p + d_p\right) + 2C_p + \frac{(D_p - d_p)^2}{C_p} \qquad (3.48)$$

The centre distance was determined using Equation 3.49 according:

$$\frac{(D_p + d_p)}{2} + d_p \le C_p \le 2(D_p + d_p) \qquad (3.49)$$

Equation 3.50 was used to determine the angle of lap (θ) of belt on pulleys, where θ is angle of contact (rads), D_d is diameter of driven pulley (cm), d_d is diameter of drive pulley (cm) and C_d is the distance between the centres of the two pulleys (mm)

$$\theta = 180 - 2Sin^{-1}\left(\frac{D_d - d_d}{C_d}\right) \qquad (3.50)$$

Tension in the slack side of the belt was calculated using Equation 3.51. In this equation, T_t is tension in the tight side (N), T_s is tension in the slack side (N), θ is angle of lap (rads), μ is coefficient of friction between belt and pulley and β is half angle of V-groove of the pulley (rads).

$$\frac{T_t}{T_s} = e^{\upsilon\theta \cos ec\beta} \tag{3.51}$$

The power transmitted per belt was determined by Equation 3.52, where P is power transmitted by the belt to cylinder during shelling (W), T_t is tension in the tight side (N), T_s is tension in the slack side (N) and v is the velocity of the belt (m/s).

$$P = (T_t - T_s)v \tag{3.52}$$

Design of shaft was based on torsion strength and torsion rigidity. Concave radius, r_c was based on the radius of curvature C_c, of the concave grate which was determined using Equation 3.53. In this equation, r_c is radius of concave (mm), r_d is radius of cylinder drum (mm), h_p is peg height above the drum (mm) and C_c is concave clearance (mm).

$$r_c = r_d + h_p + C_c \tag{3.53}$$

Measured data from the developed thresher was used to validate the performance of the developed models in simulating threshing of common beans. This was carried by plotting graphs, student *t*-test, and residual error analysis. The line of best fit, correlation coefficient, and coefficient of determination R^2 were used to measure how well simulated data compares with actual data. To establish the repeatability of experimental data, the mean and standard deviations of the data were also established. The absolute residual error ε_r was determined as shown in Equation 3.54 (Uluko *et al*., 2006; Kanali, 1997), in which ψ_p and ψ_a are the predicted and actual values, respectively. The prediction performance ($\eta_{\mu m}$) of the model at ε_r% residual error interval was determined by equation 3.55, where ς_w and ς_t represent the number of data within the interval and the total trial data, respectively. The simulated results of each performance model were validated with measured experimental outputs.

$$\varepsilon_r = \left| \frac{\psi_p - \psi_a}{\psi_a} \times 100 \right| \tag{3.54}$$

$$\eta_{um} = 100 \times \frac{\varsigma_w}{\varsigma_t} \qquad (3.55)$$

3.2 Optimizing Design Parameters and Evaluating Performance of the Common Beans Thresher

Taguchi experimental design was used to optimize the performance of the common bean thresher. This is because it resulted in optimum factor combination levels for each response. The optimization criteria were to minimize grain damage and power requirement for threshing and maximize threshing efficiency and throughput capacity. The crop characteristics whose influence on thresher performance were investigated were moisture content and bulk density. The machine and operational factors were peripheral velocity of the cylinder, feed rate, concave width and mass of the threshing cylinders. These factors were selected after analysing the variance effect on thresher performance. Table 3.4 shows selected levels of common beans and machine characteristics.

Table 3.4: Common beans and machine characteristics at different levels

Level Number	**Moisture content (%)**	**Bulk density (kg/m^3)**	**Feed Rate (kg/s)**	**Concave width (m)**	**Pegs peripheral velocity of (m/s)**	**Mass of threshing cylinder (kg)**
1	15	44	0.01	0.2	1.88	2
2	17.5	46	0.02	0.4	2.82	4
3	20	48	0.03	0.6	3.77	6
4	22.5	50	0.04	0.8	4.71	8
5	25	52	0.05	1	5.65	10

Determination of the effect of all the six factors on the performance of common beans thresher at different combination levels was carried out by selecting a matching orthogonal array. Taguchi experiment design with an orthogonal array of L_{25} (5^6) was developed to obtain results for all experiments as shown in Table 3.5. The levels were selected based on the design size of the prototype and its operational variable range i.e., operational drum speeds were in the range of 400 – 1200 rpm, which translated to a minimum pegs peripheral speed of 1.88 m/s and maximum speed of 5.65 m/s. The levels were determined based on the measurable interval quantities using the available equipment.

Table 3.5: Taguchi experiment design

Experiment No.	Peripheral velocity of the pegs (m/s)	Bulk density (kg/m^3)	Feed Rate (kg/s)	Concave width (m)	Moisture content (%)	Mass of threshing cylinder (kg)
1	1.88	44	0.01	0.2	15	2
2	1.88	46	0.02	0.4	17.5	4
3	1.88	48	0.03	0.6	20	6
4	1.88	50	0.04	0.8	22.5	8
5	1.88	52	0.05	1	25	10
6	2.82	44	0.02	0.6	22.5	10
7	2.82	46	0.03	0.8	25	2
8	2.82	48	0.04	1	15	4
9	2.82	50	0.05	0.2	17.5	6
10	2.82	52	0.1	0.4	20	8
11	3.77	44	0.03	1	17.5	8
12	3.77	46	0.04	0.2	20	10
13	3.77	48	0.05	0.4	22.5	2
14	3.77	50	0.01	0.6	25	4
15	3.77	52	0.02	0.8	15	6
16	4.71	44	0.04	0.4	25	6
17	4.71	46	0.05	0.6	15	8
18	4.71	48	0.01	0.8	17.5	10
19	4.71	50	0.02	1	20	2
20	4.71	52	0.03	0.2	22.5	4
21	5.65	44	0.05	0.8	20	4
22	5.65	46	0.01	1	22.5	6
23	5.65	48	0.02	0.2	25	8
24	5.65	50	0.03	0.4	15	10
25	5.65	52	0.04	0.6	17.5	2

The criteria for selection of the levels for moisture content was based on the standard range applicable for threshing beans of 14-25% w.b (Scariot *et al.*, 2017). Levels for bulk density were determined by experimental measurements conducted to mimic the two manual feeding process; intermittent and continuous. In addition, the levels for peripheral velocity of the pegs were selected based on safe operational drum speed to avoid excess vibration and high mechanical grain damage. Finally, the levels for mass of threshing cylinder were carefully chosen based on the effect of overall weight of the machine and the total power required for threshing.

The L_{25} orthogonal array had six columns corresponding to the factors and 25 rows for the possible combination of factor levels. Taguchi experiment design reduced the number of experiments to 25 instead of (5^6 =15,625) trials needed for six factors and a five-level factorial design. The effect of a single factor on performance output was determined by computing the average at each factor level and the results were analysed graphically. Analysis for combined factors influence was done using signal to noise ratio values. Signal to noise ratio (S/N) values were calculated for all the experiment trials. Equation 3.56 was used to calculate signal to noise ratio for performance in which low output values were expected such as grain damage and power required for threshing. The number of experimental replications in a trial was represented by n and y is the measured output value for the trial.

$$ {}^{S}/_{N} = -\,log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \qquad (3.56) $$

The S/N values for maximum outputs like throughput and threshing efficiency were determined using Equation 3.57. The higher the S/N values the better performance.

$$ {}^{S}/_{N} = -\,log\left[\frac{1}{n}\sum_{i-1}^{n} \frac{1}{y_i^2}\right] \qquad (3.57) $$

Mean S/N values were then determined for each factor level, with the highest value corresponding to the optimum desired output. The response graphs for the outputs were plotted from the results to indicate the effect of the factors under analysis on the performance of the common bean thresher. Also, to determine the contribution of each effect on the performance of the thresher, analysis of variance (ANOVA) on the S/N ratios was calculated. The S/N of simulation model data of the first 15 experimental runs is indicated in Table 3.6. The input factors at different levels were peripheral velocity of the peg (v), common beans bulk density (ρ**),** feed rate (Q), concave width (w), crop moisture content (β), and mass of the threshing cylinder. The choice of the factors was based on simulation results on the effect of the input variables on the performance of the common beans thresher. The response outputs from the simulation model were power required for threshing (P_T), grain damage (G_d), threshing efficiency (T_e), and throughput capacity (C_T).

Table 3.6: Signal to noise ratio of simulation model results

ExptRun.	**v**	**ρ**	**Q**	**w**	**β**	**M_c**	**P_T**	**S/N (P_T)**	**G_d**	**S/N (G_d)**	**T_e**	**S/N (T_e)**	**C_T**	**S/N (C_T)**
1	1.9	44	0.01	0.2	15	2	207	-46	3.4	-10.5	42.	32.5	22	26.8
2	1.9	46	0.02	0.4	18	4	285	-49	2.6	-8.3	45	32.9	37	31.5
3	1.9	48	0.03	0.6	20	6	362	-51	1.9	-5.9	47	33.4	48	33.6
4	1.9	50	0.04	0.8	23	8	439	-53	1.5	-3.3	50	33.9	57	35.1
5	1.9	52	0.05	1	25	10	517	-54	1.1	-0.6	52	34.3	65	36.2
6	2.8	44	0.02	0.6	23	10	128	-62	6.2	-15.8	84	38.4	45	33.0
7	2.8	46	0.03	0.8	25	2	361	-51	6.9	-16.7	82	38.3	63	35.9
8	2.8	48	0.04	1	15	4	592	-55	9.9	-19.9	78	37.8	75	37.5
9	2.8	50	0.05	0.2	18	6	822	-58	67	-36.6	23	27.1	88	38.8
10	2.8	52	0.1	0.4	20	8	1053	-60	1.4	-3.0	94	39.4	24	27.5
11	3.8	44	0.03	1	18	8	1972	-66	14	-23.1	94	39.5	66	36.4
12	3.8	46	0.04	0.2	20	10	2432	-68	73	-37.3	37	31.3	85	38.6
13	3.8	48	0.05	0.4	23	2	590	-55	58	-35.3	55	34.7	102	40.2
14	3.8	50	0.01	0.6	25	4	1051	-60	1.3	-2.07	99	39.9	24	27.6
15	3.8	52	0.02	0.8	15	6	1511	-63	6.9	-16.8	98	39.8	47	33.4

Expected and actual outputs were determined for this study. Expected outputs were computed from the Taguchi experiment matrix and using Equation 3.58 in which j are the number of factors, n_m is the mean of all the S/N ratios in the experimental runs and n_i is the S/N ratios corresponding to the optimum factor levels:

$$n_0 = n_m + \sum_{i=1}^{j}(n_i - n_m) \tag{3.58}$$

3.3 Development and Performance Evaluation of the Optimized Common Beans Thresher

3.3.1 Design of the optimized beans thresher

The results of optimization were used in the development of the final common beans thresher. Design analysis of optimized common beans thresher was carried out using Equation 3.45 to 3.53 to evaluate the necessary design parameters, strength and size of materials for consideration in the selection of various machine parts. Figure 3.5 shows the optimized developed common beans thresher.

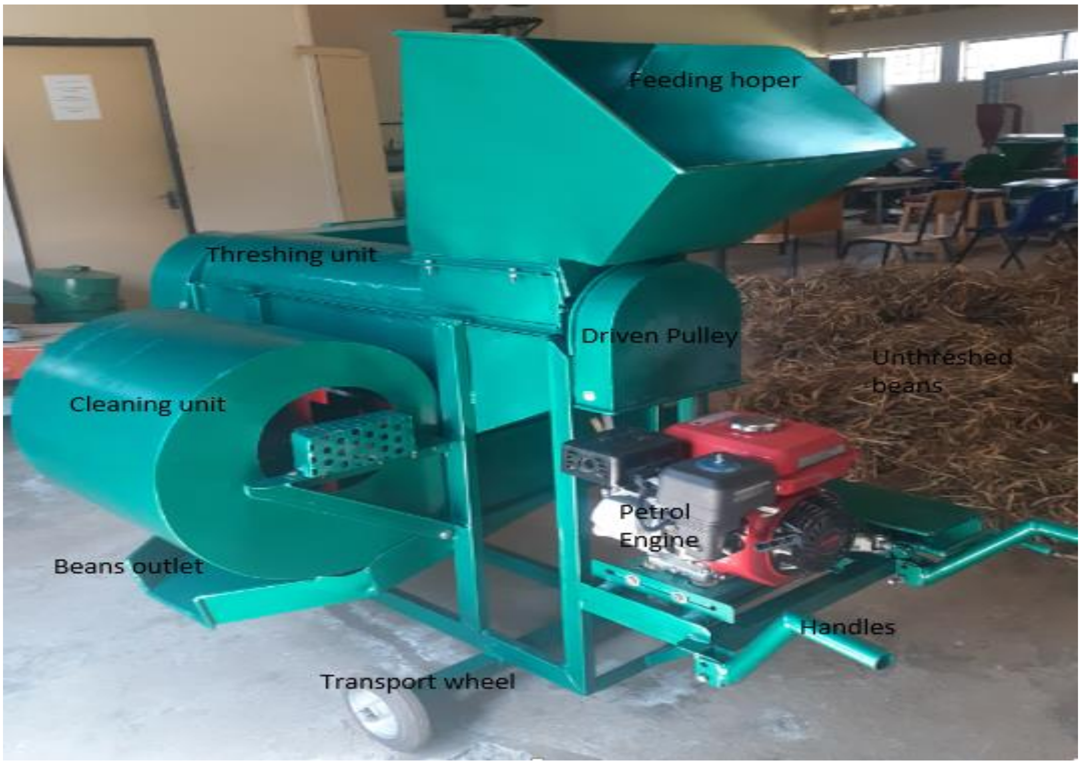


Figure 3.5: Developed portable common beans thresher.

The prototype used for validation is shown in Plate C3 in the appendices section. The main parts of the developed thresher were; feeding hopper, threshing unit, cleaning unit, driven pulley, beans outlet, chaff outlet and petrol engine. The variety of beans used for evaluation of the developed common beans thresher was the red kidney type commonly known as “Nyayo” as shown in Figure 3.6. It was selected because it is one of the main varieties grown in Kenya and also due to the large dimensions size for the design of the sieve. It was harvested in Ngongongeri farm in Egerton University (at coordinates 0.3500^{0}S, 35.9167^{0}E). This implied any other smaller bean grain variety could be threshed by the same machine considering the size of the aperture for sieves used. Maximum length of the bean straw after harvesting was measured. This was important in the design of the drum diameter to avoid winding of the straw that can cause seizure of the machine during operation. Moisture content was also determined using the oven drying method.

Figure 3.6: Threshed "Nyayo" common bean (Phaseolus Vulgaris L) variety.

The design specification of the bean thresher were: Effective cylinder diameter of 200 mm, drum diameter of 160 mm, total length of shaft of 1000 mm, radius of the driven pulley of 100 mm, throughput capacity of 150 kg/hr, height of the machine to the feeding hopper of 1540 mm, total mass of the machine of 70 kg, Maximum length of machine of 1200 mm, both side thickness of frame, threshing drum length, cam thickness, drum to frame spacing, and the thickness of both pulleys supported by both end of the shaft. Direction of shaft rotation should counter clock wise according to the industrial standard of metric system. Estimated cost of the machine is Ksh. 70,000. Grain size and morphology of common beans were: common beans length of 19.96 mm, grain width of 8.97 mm, grain thickness of 7.6 mm, grain geometric diameter of 8.35 to 9.66 mm, angle of response of 35 to 40 degrees, grain densities = 709 to 766 kg/m^3 at 21% moisture content and average grain straw ratio of 0.588 to 0.925. The design drawing is shown in Place C4 in the appendices.

3.3.2 Evaluating the Performance of the optimised beans thresher

Equipment used during evaluation were digital stopwatch timer (QIUSHUO, China), Kusam Meco Contact Tachometer (KM-2235B, India), Hochoice digital weighing balance with accuracy of 0.01g sensitive (Shanghai Huachao Industrial Company Ltd, China) and a generic power watt voltage meter monitor (GE840IP1H4Q2PNAFAMZ, China). Harvested dried common beans were fed into the thresher operating at known drum speed and time taken for the threshing process was noted. The power consumption during threshing time was also noted. All grains and chaff materials at the outlets were collected and weighed.

To determine threshing efficiency, three samples each of about 3000 g of unthreshed material was threshed. The clean grain was then weighed on an electronic balance. The unthreshed grains was manually plucked by hand, cleaned and weighed. The threshing efficiency was then calculated using Equation 3.59, where M_t is mass of threshed grain (kg) and M_u is mass of unthreshed grains (kg).

$$\eta = \left(1 - \frac{M_u}{M_t + M_u}\right) \times 100 \tag{3.59}$$

Mechanical grain damage was established by visual observation of the cracked bean grains out of the 3000 g threshed grains. Damaged grain was sorted out manually and weighed. Percentage of damaged grain (G_d) was calculated using Equation 3.60, where M_d is mass of damaged grains (g), and M_t is mass of threshed grain (g).

$$G_d = \frac{M_d}{M_t} \times 100 \tag{3.60}$$

Finally, throughput capacity was determined by weighing the total grain (whole and damaged) received per hour at main grain output of the thresher. The throughput per unit energy consumed was calculated using Equation 3.61, where M_t is mass of threshed grain (kg), P_t is electric power consumed (kWh) and t is time of test run (h).

$$f = \frac{M_t}{P_t} \tag{3.61}$$

To determine the cleaning efficiency, 3000 g sample was weighed. The sample was cleaned again by separation. After cleaning the grain and chaff was weighed and the cleaning efficiency of the thresher was determined using the following Equation 3.62. In this equation, C.E. is cleaning efficiency in percentage, w is weight of chaff in the sample and W is the total grain sample taken, 3000 g.

$$C.E = \frac{W - w}{W} \times 100 \tag{3.62}$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Simulation of Effect of Design Parameters on Performance of Common Beans Thresher

Modelling and simulation were used to study and understand the effect of design variables (i.e., peripheral speed of threshing pegs, feed rate, moisture content of unthreshed beans, concave clearance and linear concave width) on the performance of a common beans thresher. The performance indicators for the thresher included power requirement, mechanical grain damage, threshing efficiency and throughput capacity. The correlation measures between variables used in this study were as follows: 0 to less than 0.4, very weak; 0.4 to less than 0.6, weak; 0.6 to less than 0.8, strong; and 0.8-1.0, very strong.

4.1.1 Effect of peripheral speed of threshing pegs on power requirement

Figure 4.1 compares simulated and actual power requirements for the common bean thresher for various peripheral speeds of threshing pegs. The results show that there was a strong linear correlation between power required and threshing speed for both simulated and actual data since the coefficients of determination (R^2) were 0.987 and 0.968, respectively. The power required increased from 208 and 276 W to 589 and 537 W for simulated and actual data as the threshing speed increased from 1.88 to 5.65m/s, respectively. The corresponding mean power requirements were 375.5±130.5 and 384.0±95.1 W for simulated and actual data. The linear relationship between power required and threshing speed observed above could be attributed to the fact that power required is mainly a function of cylinder rotation, grain detachment and frictional forces (Ndirika 2006). Therefore, increasing speed resulted in increased power required for threshing. The trend was similar to the results by Ndirika (1997) that predicted power requirement and threshing efficiency using mathematical model for sorghum and millet. Similar trends were also observed by

Vejasit & Salokhe (2004) who conducted studies on machine crop parameters of an axial flow thresher for threshing soybean with different moisture content of 14.34 to 22.77% (w.b.) and feed rate of 540 to 720 kg (plant)/h. In this study, a constant moisture content of 21% (w.b) was used in simulation. The power increase was due to greater compression of the material and increased friction between crop material and threshing system.

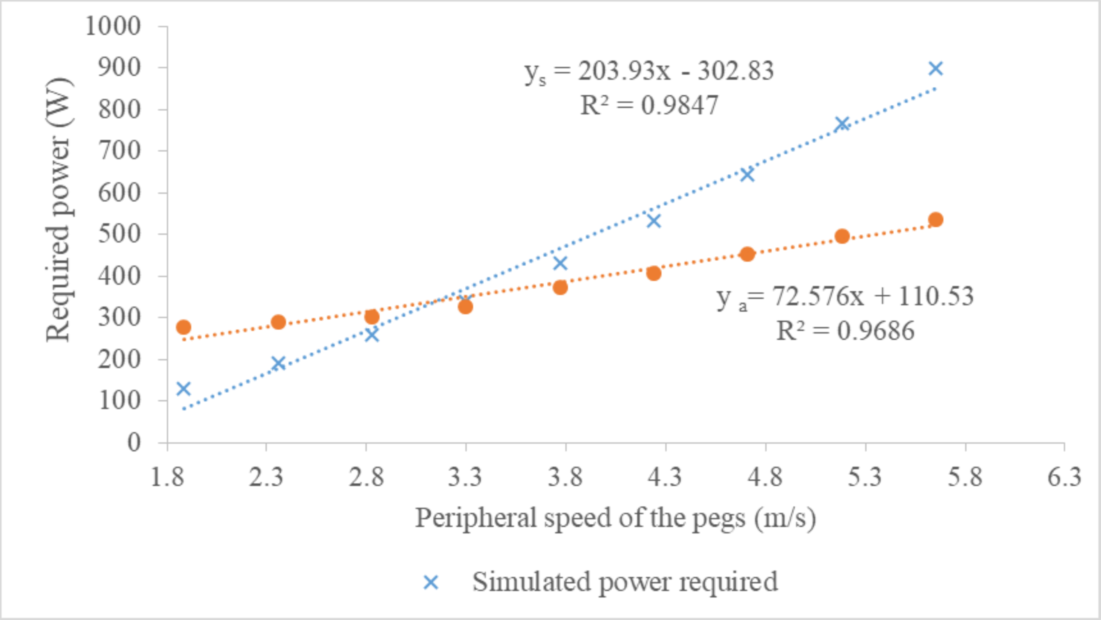


Figure 4.1: Comparison of simulated and actual power required for threshing common beans for varying peripheral speed of pegs.

In the figure: y_s, simulated power; y_a, actual power

The relation between simulated and actual power required for threshing common beans is presented in Figure 4.2. The results show that there was a very strong positive linear correlation between simulated and actual power required as R^2 was 0.993. This implies that the developed simulation model can be used for predicting power required for threshing common beans.

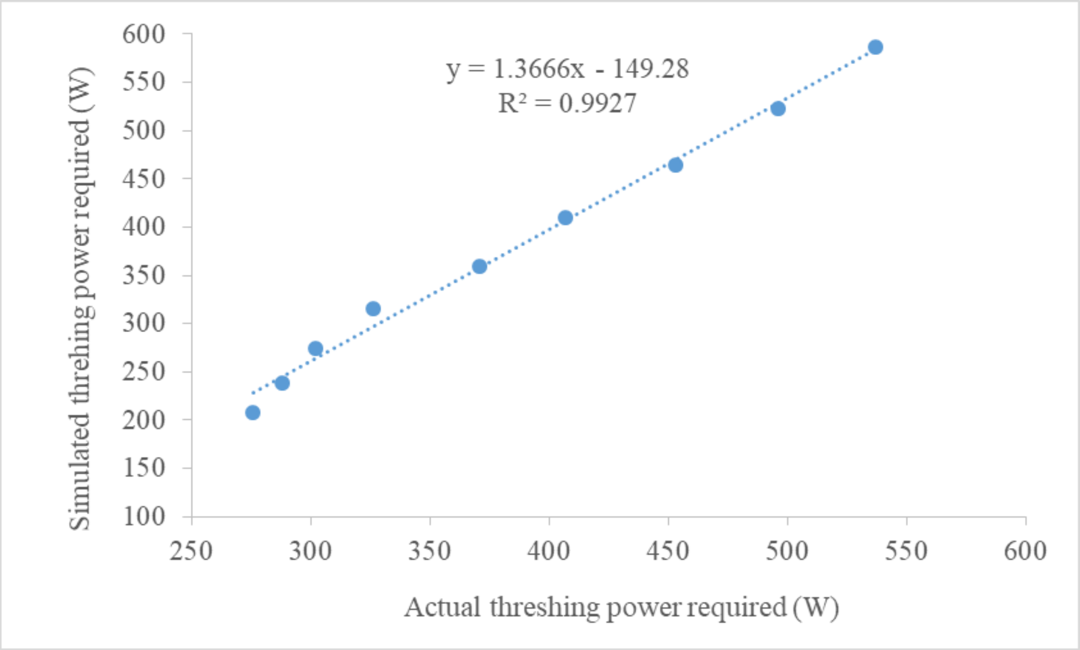


Figure 4.2: Relation between simulated and actual power required for threshing common beans.

Similarly, when the student t-test for paired two sample means between simulated and actual data was conducted on the data presented in Table B11 in the appendices, a t-statistics at 5% of 0.69 was obtained, which is less than t-critical of 1.89. This also shows that there is no statistically significant difference between simulated and actual data and thus validating the model for use in predicting power required for threshing beans.

The absolute residual error between simulated and actual power required for threshing the beans ranged between 0.7 and 9.2%, with a mean value of 4.4±10.9% (Table 4.1). Based on a 10% absolute residual error interval the computed prediction performance, equation (3.46), of the model was 77.8%. Residual error values within the 10% interval corresponded to peripheral speeds lying between 2.83 and 5.65 m/s while higher error values were obtained for speeds below 2.8 m/s. This implies that the threshing speed of the pegs should be set to be within 2.8 and 5.7 m/s to obtain accurate power prediction using the simulation model. The higher power requirement for the prototype could be because of the used synchronous motor that was connected to fixed frequency source of power. They need more current to start, because the induced frequency in the rotor is high.

Table 4.1: Absolute residual error for simulated and actual power required for threshing common beans

Peripheral pegs velocity (m/s)	Simulated power required (W)	Actual power required (W)	Absolute residual error (%)
1.88	207.8	276	24.7
2.36	238.9	288	17.1
2.83	274.6	302	9.1
3.30	315.0	326	3.4
3.77	360.0	371	3.0
4.24	409.7	407	0.7
4.71	464.0	453	2.4
5.18	523.0	496	5.4
5.65	586.6	537	9.2
Mean residual error			4.4±10.9
Prediction performance at 10% residual interval			77.8

4.1.2 Effect of peripheral speed of threshing pegs on mechanical grain damage

Figure 4.3 shows the results of simulated and actual mechanical bean damage at different peripheral speeds of threshing pegs. The results show that grain damage increased rapidly in an exponential manner with increase in threshing speed within the speed range of 2.83 and 5.65 m/s. This is because, cylinder velocity and minimum velocity to cause grain damage are some of the key variables of importance influencing damage parameter. Therefore, rapid increase in grain damage with increase in speed is due to the fact that the impact force enough to cause damage increased rapidly with increase in speed (Olaye *et al*., 2016). There is also a very strong positive exponential correlation between grain damage and threshing speed as the R^2 values were 0.914 and 0.870 for simulated and actual data, respectively. This implies that the developed simulation model can be used to predict grain damage for threshing common beans. The results also show that mechanical bean damage was higher for the actual than simulated model. This is because of the fabrication mistake of the prototype that was observed during data collection. The clearance of the prototype was designed at 22 mm but because of the wrong alignment of the drum the clearance reduced to less than 16 mm causing increased grain damage and therefore, necessitating further improvement of the prototype thresher.

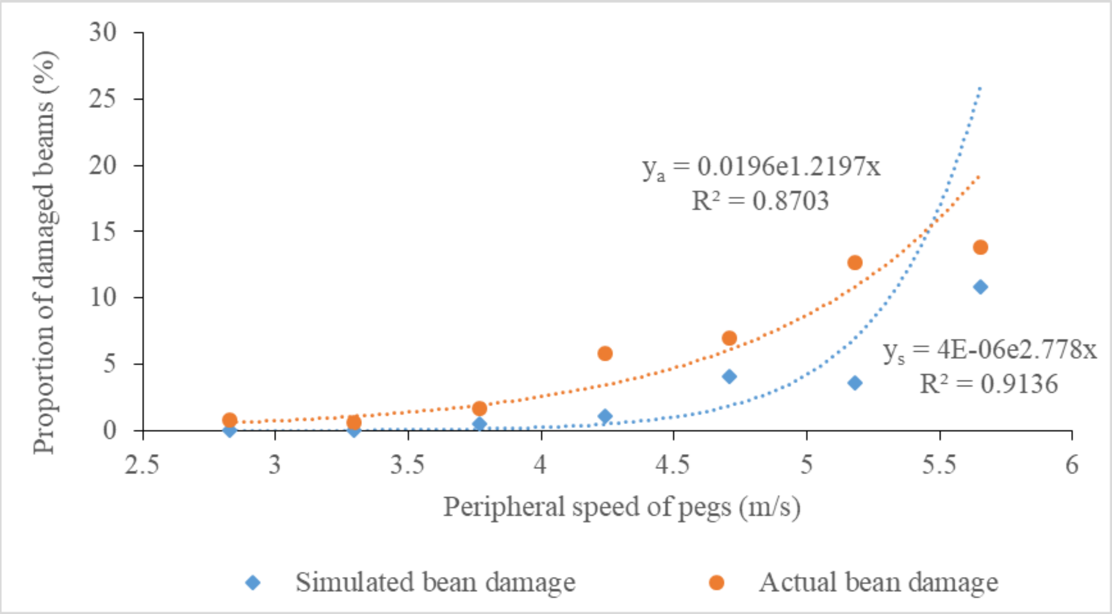


Figure 4.3: Proportion of damaged beans for simulated and actual data for different peg peripheral speeds.

The results further show that there was hardly any mechanical bean damage for peripheral peg speeds below 2.83 m/s for both simulated and actual data (Appendix B19). This could be due to the low impact force created by the pegs at speeds below 2.83 m/s that is not enough to cause mechanical grain damage. However, the bean damage increased significantly to 10.9 and 13.8% at a threshing speed of 5.65 m/s for simulated and actual data. The mean bean damage values were 2.27±3.61 and 4.71±5.47% for simulated and actual data which are higher than the recommended value. According to the United States Department of Agriculture, the recommended maximum total damaged grain is 2% for grade one grains of soybeans. Therefore, performance optimization of the thresher was necessary to reduce grain damage.

It was observed that the beans split into two halves as they got damaged due to the dichotomy nature of bean which is a point of weakness. Therefore, increase in cylinder pegs' peripheral velocity, resulted to increased impact force enough to cause grain damage starting with the section between the cotyledon (Osueke, 2011). The trend was similar to Khazaei (2009) who studied influence of impact velocity and moisture content on mechanical damages of white kidney beans under loadings. The results showed that impact velocity influenced the physical damages of kidney beans at 1% and 5% level of significance, respectively. Increasing the impact velocity from 5 to 12 m/s caused an increase in the mean percent of physical damages from 3.25 to 37.5%.

The relationship between simulated and actual mechanical bean damage is presented in in Figure 4.4. The results show that there was a strong positive linear correlation between simulated and actual bean damage since R^2 is 0.757. This implies that in as much as there was a strong positive correlation between simulated and actual bean damage during threshing, there was also some disparity. This could be because of fabrication inaccuracies of the prototype thresher, especially with regard to the concave and sieve dimensions (Gbabo *et al.*, 2013).

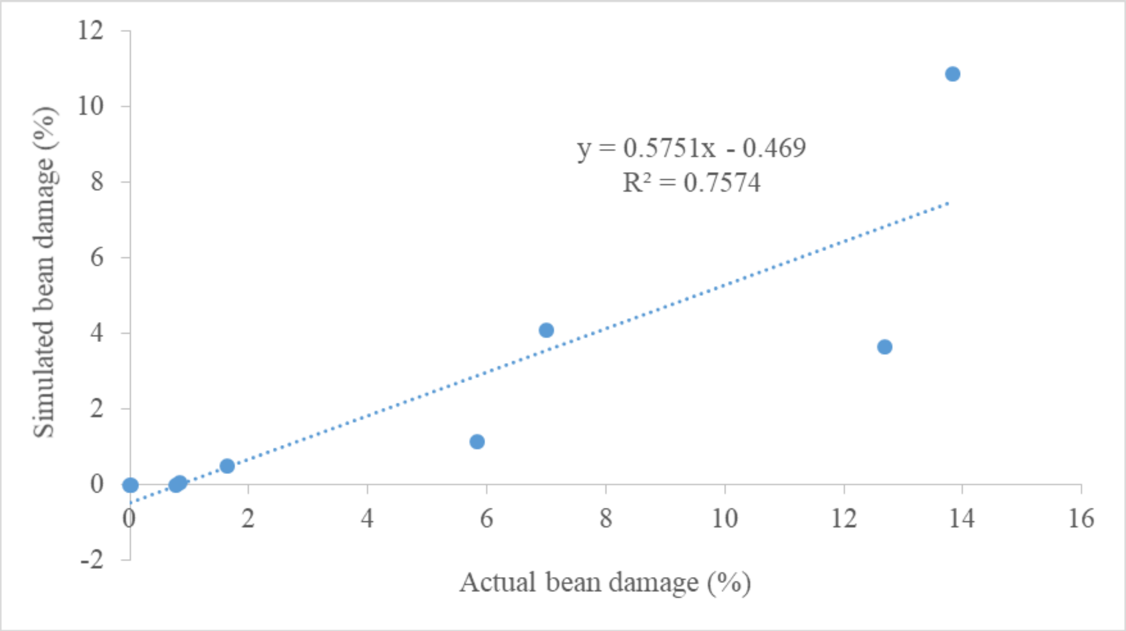


Figure 4.4: Relation between simulated and actual mechanical bean damage.

A Student t-test was also conducted on the two sets of paired means as shown in Table B12 in the appendices, resulting in t_{stat} at 5% level of significance of 2.55 which is greater than $t_{critical}$ of 1.86, indicating that there was statistically significant difference between simulated and actual data. This was true because outliers occurred at high peg peripheral speed for the actual bean damage due to incorrect concave clearances for the prototype thresher. Abich (2018) recommends that shape of the cylinder pegs should be smoothened, and sieve size increased to allow free fall of the bean grains through the concave surface.

The absolute residual error between the simulated and actual damaged beans ranged from 0.2 to 18.6%, with a mean value of 7.2±7.0% (Table 4.2). This implies there was some disparities between the simulated and actual data on a few peripheral velocities of the pegs. The results show that, at 10% residual error interval, the prediction performance of the simulation model was 77.8%, implying that there was still some discrepancy between actual and the simulated data. Further improvements on the prototype thresher were thus recommended. Mechanical grain damage is a critical performance indicator for cereal grain threshers (Osueke, 2014). It has a direct effect on the germination of seeds and commercial value of beans.

Table 4.2: Absolute residual error for simulated and actual damaged beans

Peripheral pegs velocity (m/s)	Simulated damaged beans (%)	Actual damaged beans (%)	Absolute residual error (%)
1.88	0	0.00	0.4
2.36	0	0.02	18.6
2.83	0	0.77	0.3
3.30	0.06	0.84	7.9
3.77	0.49	1.64	18.2
4.24	1.14	5.83	3.4
4.71	4.1	7.00	8.4
5.18	3.66	12.69	2.3
5.65	10.85	13.83	5.7
Mean residual error			7.2±7.0
Prediction performance at 10% residual interval			77.8

4.1.3 Effect of peripheral speed of threshing pegs on threshing efficiency

Figure 4.5 shows actual and simulated threshing efficiency of common beans thresher under different peg peripheral speeds. The results show that threshing efficiency increases with increase in threshing speed, and there is a positive logarithmic correlation between the two variables. The R^2 values obtained are 0.646 and 0.988 for simulated and actual data, respectively, indicating that there are strong and very strong correlation between threshing efficiency and threshing speed. The threshing efficiency increased from 94.3 to 97.2%, and from 98.0 to 100.0% between 1.88 to 5.65 m/s for simulated and actual data, respectively. This can be explained on the basis that at higher velocity, threshing of common beans by impact and rubbing is enhanced (Osueke, 2011). In addition, bean grains are detached from pods by combination of stripping, rubbing and impact action that are increased with increase in speed. This action involves the application of tensile, compressive, bending and twisting forces on a head of grain by pegs in motion (Ndirika, 1997). The trend observed above is similar to of Osueke (2011) who developed mathematical model for threshing efficiency to predict mean rate of threshing of grain as a function of the number and energy level of impact of the unthreshed material. The results showed that as velocity increases, the threshing efficiency increased in all model cases including the one developed by for Huynh *et al.*, (1982). It was found that as the velocity increases, the threshing efficiency increases from 96.3% at 9 m/s to 97.3% at 25 m/s.

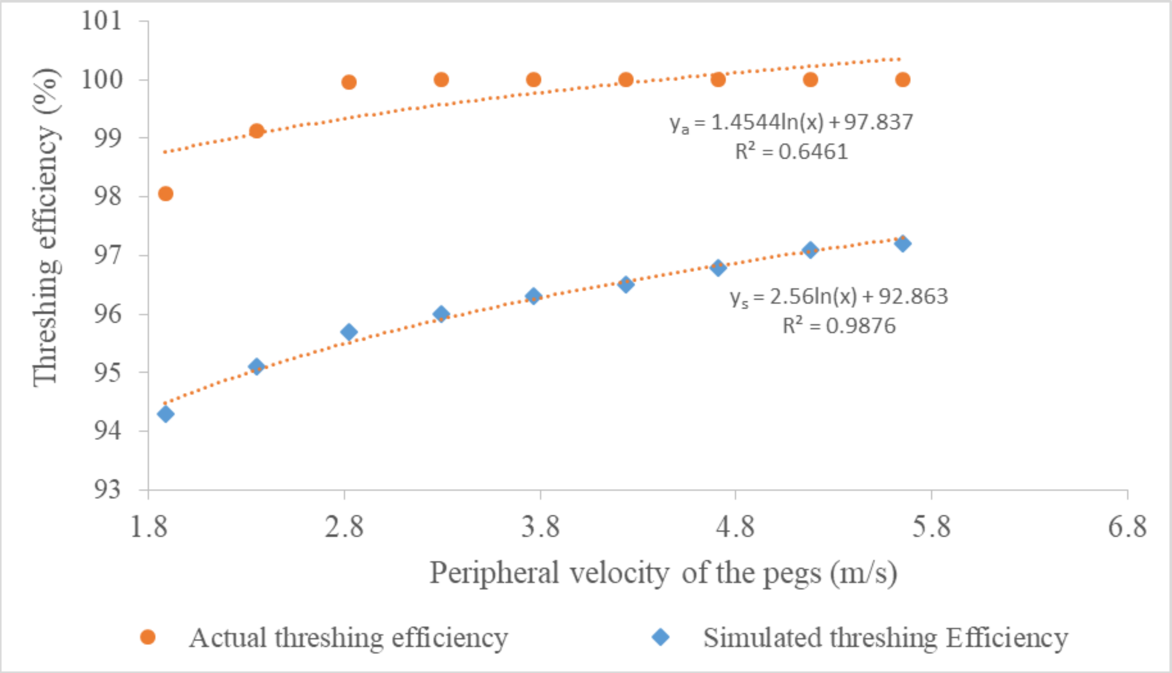


Figure 4.5: Comparison of simulated and actual threshing efficiency for different thresher peg peripheral speeds.

The relation between simulated and actual threshing efficiency is presented in Figure 4.6. The R^2 obtained was 0.738 indicating that there was a strong positive linear correlation between simulated and actual data. Again, in as much as there was strong correlation between the two data sets, there were some few differences which warrant determining whether or not the prototype thresher was operating at its optimal condition.

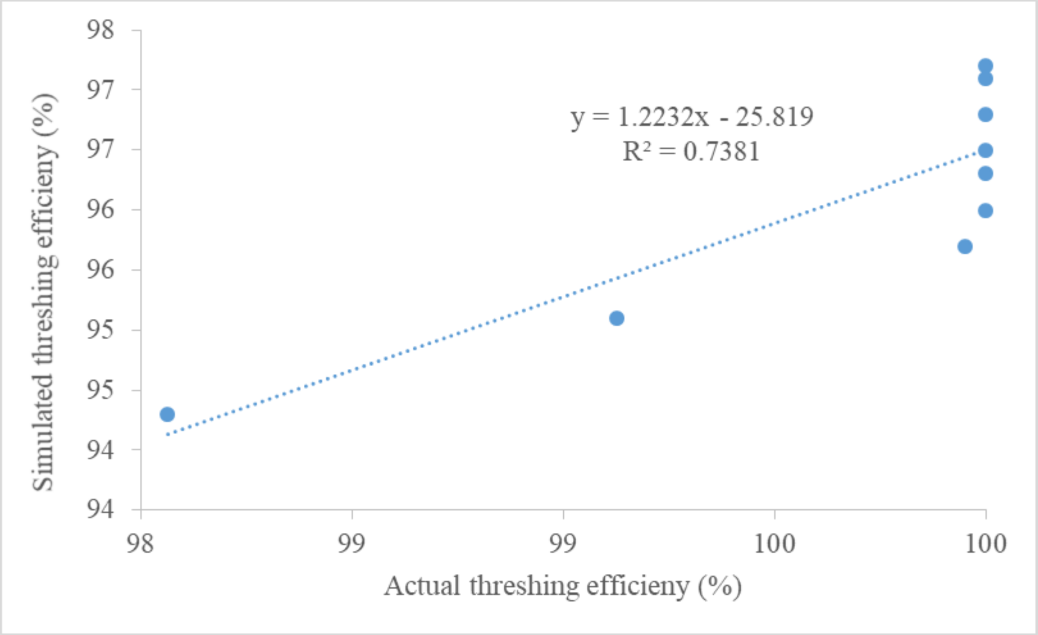


Figure 4.6: Relation between simulated and actual threshing efficiency.

Student t-test results show that there was significant difference between simulated and actual data as t-stat at 5% was 20.9 compared t-critical of 1.85 (Table B13 in the appendices). This could be attributed to crop characteristics that require little impact force for threshing dried common beans (Chansrakoo & Chuan, 2018).

The absolute residual error between the simulated and actual threshing efficiency ranged from 2.8 to 4.5%, with a mean value of 3.6±0.5% as shown in Table 4.3. This means that at 5 and 10% residual error interval, the prediction performance of the simulation model for threshing efficiency was 100%. Therefore, the model can be used to accurately predict threshing efficiency.

Table 4.3: Absolute residual error for simulated and actual threshing efficiency

Peripheral pegs velocity (m/s)	**Actual threshing efficiency (%)**	**Simulated threshing efficiency (%)**	**Absolute residual error (%)**
1.88	98.1	94.3	3.8
2.36	99.1	95.1	4.1
2.83	100.0	95.7	4.3
3.30	100.0	96.0	4.0
3.77	100.0	96.3	3.7
4.24	100.0	96.5	3.5
4.71	100.0	96.8	3.2
5.18	100.0	97.1	2.9
5.65	100.0	97.2	2.8
Mean residual error			3.6±0.5
Prediction performance at 5 and 10% residual interval			100.0

4.1.4 Effect of peripheral speed of threshing pegs on thresher throughput capacity

Figure 4.7 shows results of simulated and actual throughput capacity of common beans thresher under different speeds of threshing pegs. The result show that there was a strong positive linear correlation between throughput capacity and threshing peripheral speed of pegs for both simulated (R^2 = 0.951) and actual (R^2 = 0.928) throughput capacity. This is because throughput capacity is mainly a function of speed, feed rate and drum volume which remains constant during operation. The observed trend was similar to that by Ndirika (2006) who developed a mathematical model for predicting output capacity of selected stationary spike-tooth grain threshers. The model was verified and validated by fitting it into established experimental data from stationary mechanical millet thresher. The results showed that there was an increase in output capacity with increase in drum speed. The results further revealed that the fitted model correlated well with the experimental data with R^2 value of 0.99. In addition, the results are also similar to the findings by Olaoye *et al*. (2010). This is backed by the fact that the velocity of pegs, grain-straw ratio, bulk density, feed rate, separation efficiency, and concave configurations affected grain threshers' output capacity (Behera *et al*., 1990; Enaburekhan, 1994; Ndirika, 1997).

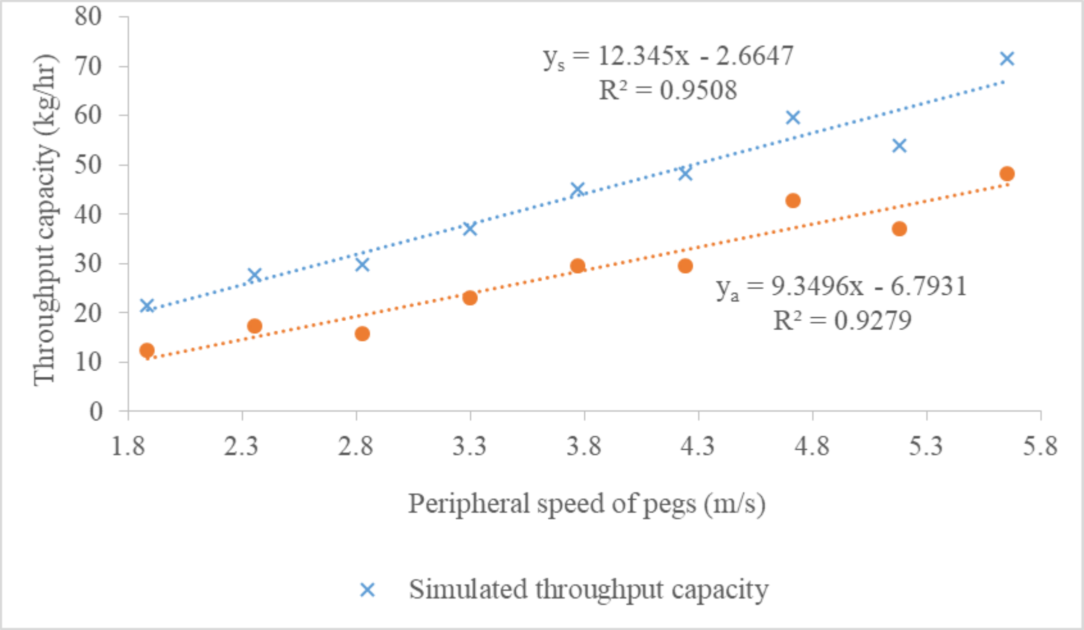


Figure 4.7: Comparison of simulated and actual thresher throughput capacity under different peripheral speed of pegs.

The relation between simulated and actual throughput capacity is presented in Figure 4.8. The results show that there is a very strong correlation between simulated and actual throughput as R^2 is 0.985. This means that 98.5% of variations for simulated throughput capacity was explained with variation of actual throughput capacity. Therefore, the simulation model can be used to accurately predict actual throughput capacity.

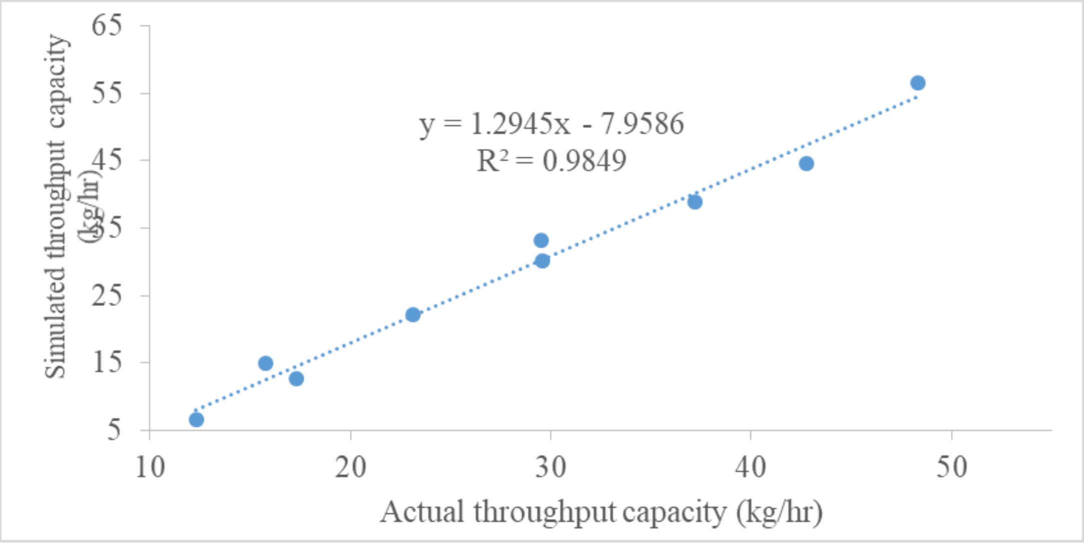


Figure 4.8: Relation between simulated and actual throughput capacity.

A Student *t*-test was also conducted to check if there was significant difference between simulated and actual thresher throughput capacity (Table B14 in the appendices). The t-stat obtained at 5% is 0.29, a value less than t-critical of 1.89, an indication that there was no significant difference between the two data sets. The results of absolute residual error between simulated and actual throughput capacity are presented in Table 4.4. The absolute residual errors were within 10% interval for peripheral peg speeds lying between 2.83 and 5.65 m/s and this represented 77.8% prediction performance. This implies that there were some disparities between simulated and actual throughput capacity, especially for threshing speeds below 2.83 m/s. This could be as a result of the incorrect alignment of the drum for the prototype that affected the cylinder volume that is a key factor affecting throughput capacity. As already mentioned, traditional methods of threshing that involve using sticks and animals are slow and tedious. Therefore, simulation of throughput capacity during design and development of common bean thresher was key for further optimization.

Table 4.4: Absolute residual error for simulated and actual throughput capacity

Peripheral pegs velocity, m/s	**Simulated throughput**	**Actual throughput capacity, kg/hr**	**Absolute residual**

	capacity, kg/hr		error, %
1.88	6.6	12.3	46.1
2.36	12.7	17.3	26.9
2.83	14.9	15.8	5.7
3.30	22.1	23.1	4.5
3.77	30.2	29.6	2.2
4.24	33.2	29.5	8.3
4.71	44.7	42.8	4.4
5.18	38.9	37.2	4.6
5.65	56.5	48.3	9.9
Mean residual error			8.1±14.6
Prediction performance at 10% residual interval			77. 8

4.1.5 Effect of moisture content of unthreshed beans on bean grain damage and threshing efficiency

The results for moisture content were 56.7 and 46.6% (w.b) for unthreshed common beans and bean grains after harvesting from the farm, respectively. After sun drying, the moisture content reduced to 18.7 and 17.6% for unthreshed common beans and bean grains, respectively. Using a moisture content range of 15 to 35%, the performance of the bean thresher was determined through simulation. Figure 4.9 shows the relationship between threshing efficiency and moisture content, and grain damage and moisture content for simulated data for unthreshed beans. The results show that there was a very strong negative linear correlation (R^2 = 0.906) between threshing efficiency and moisture content. This means that 90.6% of variations for threshing efficiency was explained with variation of moisture content. Increase in moisture content from 15 to 35% resulted to decrease in threshing efficiency from 99.8 to 95.6%. This because during threshing, the bean grains are detached from the pods by a combination of stripping, rubbing, and impact action through the application of tensile, compressive, bending, and twisting forces. However, this is not effective at high moisture content (Simonyan and Yijep, 2008). Similar trends were observed by Osueke (2011), who determined the effect of moisture content on threshing efficiency between 10-25% moisture levels. The results indicated that there was a decrease in threshing efficiency with increased moisture content. However, the crop used in simulation is not stated for verification.

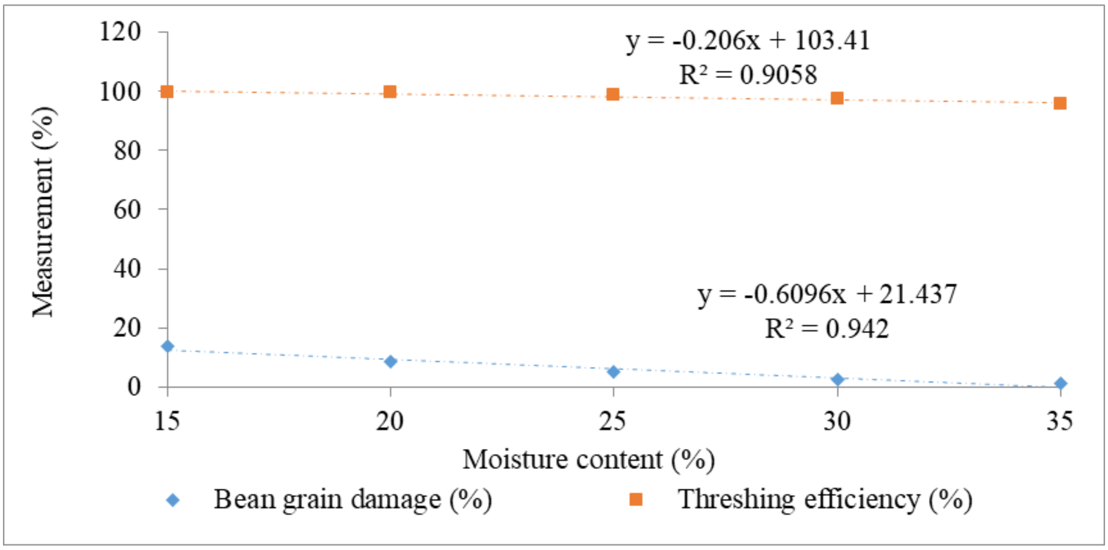


Figure 4.9: Effect of moisture content on threshing efficiency and bean grain damage.

The results in Figure 4.9 also show that there was a very strong negative linear correlation between mechanical bean damage and moisture content as R^2 was 0.942. Increased moisture content caused decrease of damaged common bean grains in the range of 15-35% moisture content. This could be because of the slippery nature of beans with high moisture content that reduces impact force of the pegs. Therefore, this necessitated optimization of the prototype thresher to achieve high threshing efficiency with the lowest grain damages. The results were similar to those by Khazaei (2008) who found that increasing moisture content from 5 to 15% (wet basis), the mean values of the percent of damaged beans decreased by 1.4 times.

4.1.6 Effect of concave clearance on threshing efficiency and bean grain damage

Figure 4.10 shows the results of simulating concave clearance on threshing efficiency and bean grain damage. The results show that there was a very strong (R^2 = 0.946) negative linear correlation between threshing efficiency and concave clearance. Increase in concave clearance from 0.02 to 0.024 m decreased threshing efficiency from 97 to 69%. This is because the impact and rubbing action is reduced with increased concave clearance which resulted to decreased threshing efficiency (Ndirika, 1997).

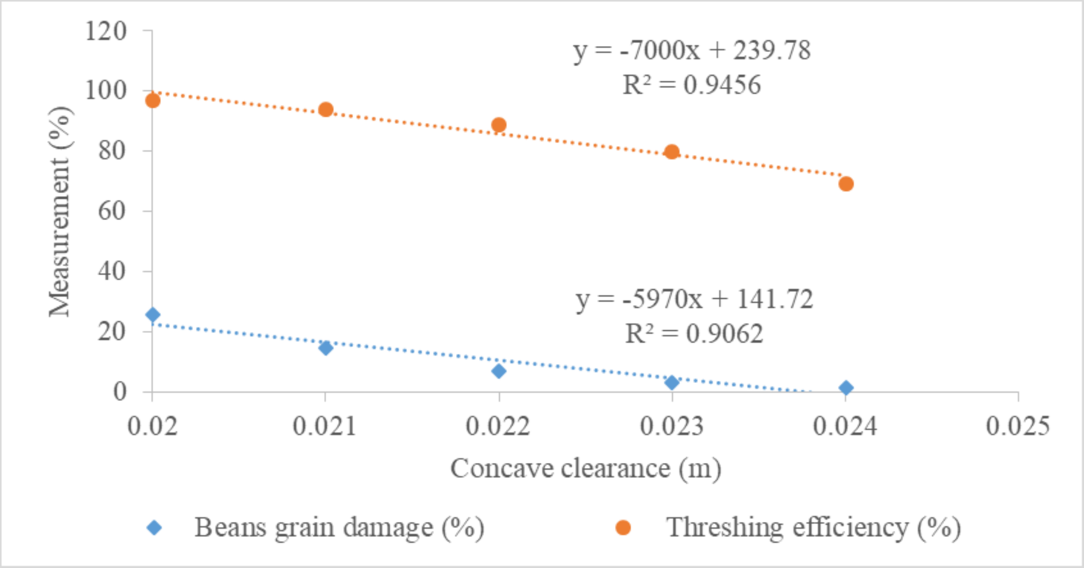


Figure 4.10: Effect of concave clearance on threshing efficiency and bean grain damage.

Similar outcomes were observed by Osueke (2011) who reported that decreasing the concave clearance resulted to increased efficiency. This was because decreasing concave clearance may have increased the chance of a grain being struck by the pegs and increased the chance of multiple impacts to the grain before it is passed from the threshing zone. The results in Figure 4.10 also show that there was a very strong (R^2 = 0.906) negative linear correlation between mechanical bean damage and concave clearance. Increased concave clearance from 0.02 to 0.024 m resulted to decrease in bean grain damaged from 25.6 to 1.6%. Rubbing and impact action increased with reduced concave clearance leading to increased bean gain damage (Ndirika, 2006). Therefore, the choice of the correct concave clearance is very key in the reduction of grain damage. Further improvement of the prototype thresher was necessary through optimization to determine the correct cylinder-concave configuration.

4.17 Effect of linear concave width on threshing efficiency

Figure 4.11 shows the effect of linear concave width on threshing efficiency of the common bean thresher. A linear span of 1 m concave width was divided into quarters of 0.25 m and data collected at each point. The results shows that there was a very strong linear correlation (R^2 = 0.972) between threshing efficiency and linear concave width. An increase in linear concave width from 0.25 to 0.95 m resulted in increase in threshing efficiency from 25.4 to 94.1%. This was justified by the increased exposure time of the unthreshed bean pods to impact, twisting, and rubbing action within the concave area (Khazaei, 2009).

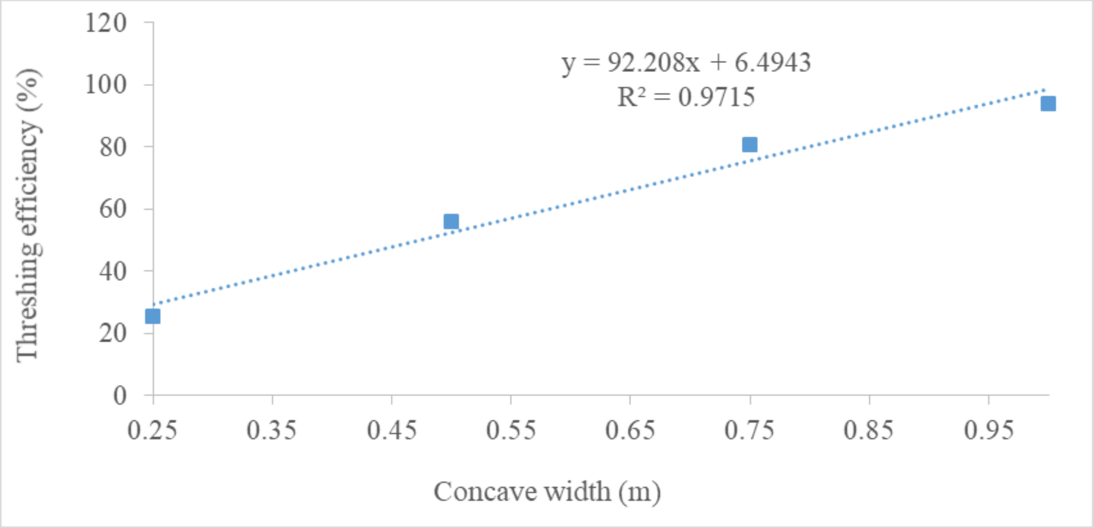


Figure 4.11: Effect of linear concave width on threshing efficiency.

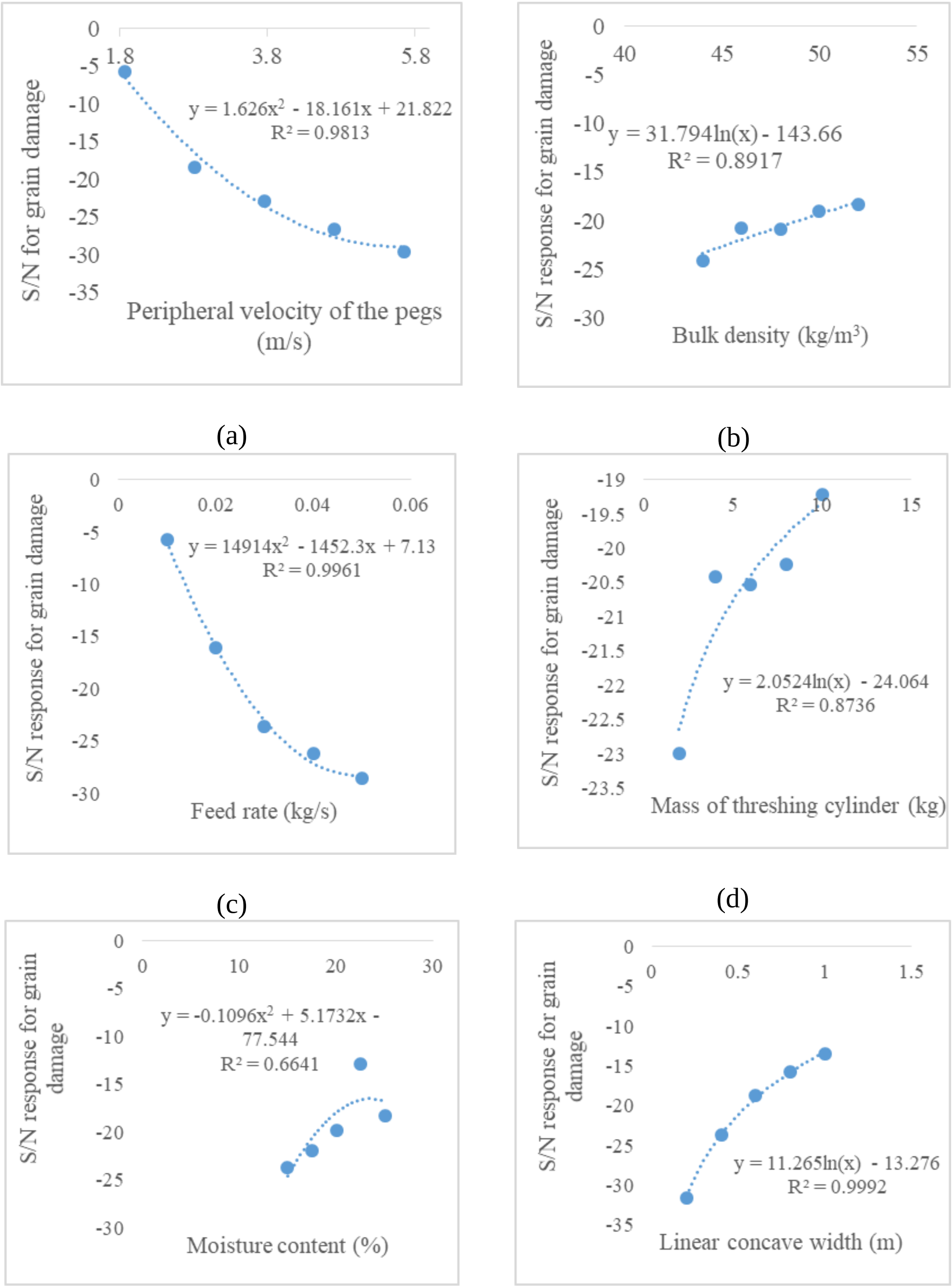
These results indicate that for the design of a common bean thresher, the linear concave width should be equal to or greater than 1m to attain high threshing efficiency. During design, the determination of the correct and effective concave width was a key factor.

4.2 Optimized Performance of Common Beans Thresher

The main goal in this section was to determine factor combination levels that yielded optimum threshing efficiency, throughput capacity, power required for threshing, and mechanical bean grain damage. Optimization was conducted on a model of a real system and therefore, sizing of design variables and parameters beyond what could be achieved practically was made possible. The section outlines the results of the optimization process.

4.2.1 Mean signal to noise ratio values and response curves

Figure 4.12 shows signal to noise ratio (S/N) response for bean grain damage for various thresher design and bean parameters. The results in Figure 4.12(a) show that there is a very strong ($R^2 = 0.981$) negative polynomial correlation between S/N response for bean grain damage and peg peripheral speed. It is noted that increase in peg peripheral speed from 1.88 to 5.65 m/s decreased S/N response for bean grain damage from -5.7 to -29.5. Therefore, using the concept of the higher S/N ratio corresponding to an optimal level (Karna *et al*., (2012), a peripheral peg speed of 1.88 m/s was found to be optimal for grain damage. This is because, at low speed, the impact and frictional force are low to cause any damage to the grains (Chen *et al*., 2021). On the other hand, the results in Figure 4.12(b) show that there is a very strong ($R^2 = 0.942$) positive logarithmic correlation between S/N response for bean grain damage and bulk density of unthreshed common beans. As bulk density increases from 44 to 52 kg/m^3, S/N response for bean grain damage increases from -24.1 to -18.4. The optimal bulk density of unthreshed common beans for grain damage as shown in the Figure 4.12 (b) was 52 kg/m^3.based on the higher S/N ratio. The value was similar to the actual bulk density during experimental threshing.



(a) (b)

(c) (d)

(e) (f)

Figure 4.12: Signal to noise ratio response for bean grain damage for various thresher design and bean parameters.

In the figure: S/N, signal to noise ratio

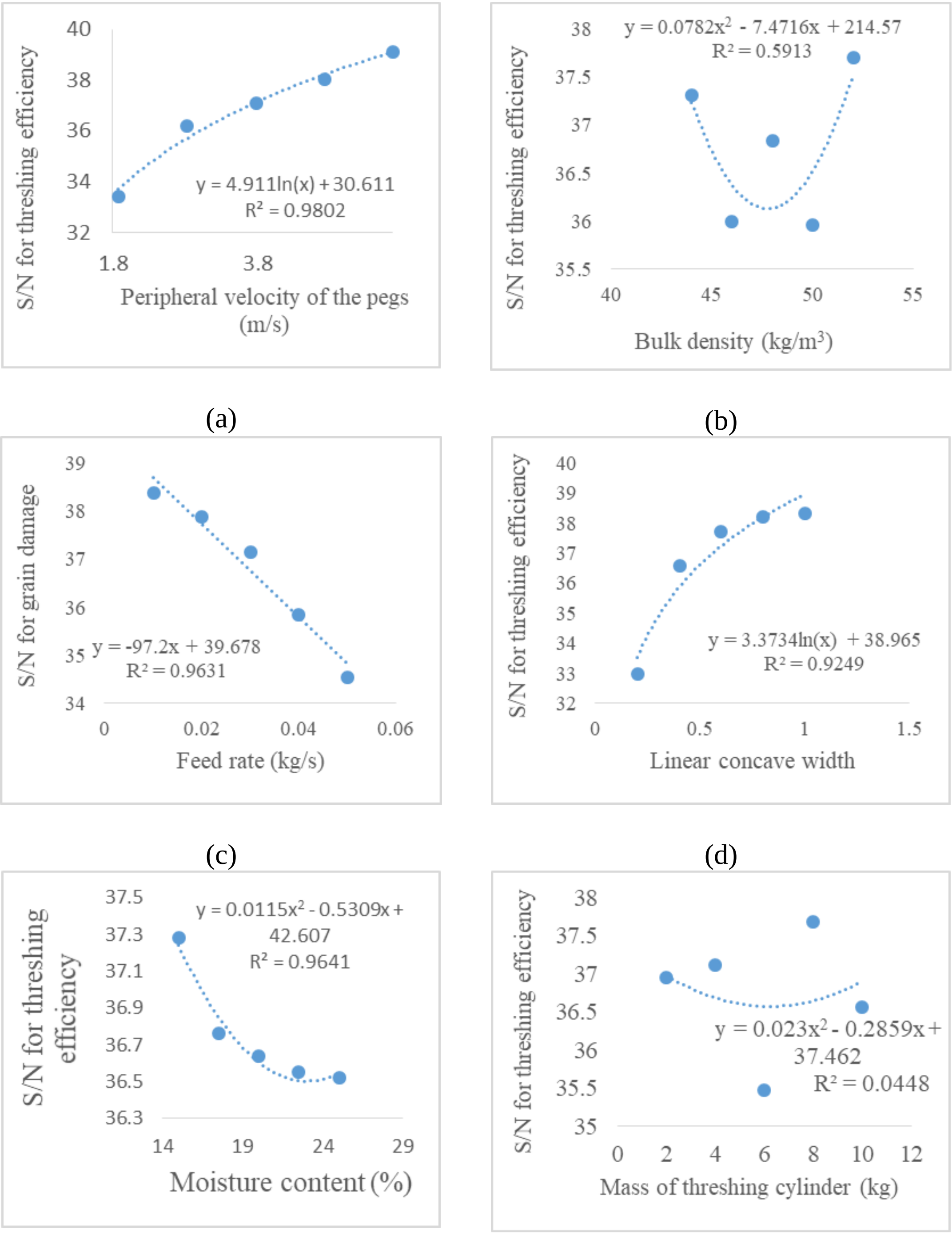
There is a very strong (R^2 = 0.996) negative polynomial correlation between S/N response for bean grain damage and feed rate of unthreshed common beans in the thresher (Figure 4.12(c)). It is noticed that S/N response for bean grain damage decreased from -5.8 to -28.6 with increase in feed rate from 0.01 to 0.05 kg/s. The feed rate level of 0.01 kg/s was found to be optimal as it corresponded to the highest S/N ratio for bean grain damage. Feed rate is a factor of the peripheral speed of pegs, therefore due to proportionality, low-speed results in low feed rate which causes low bean grain damage. In addition, the results in Figure 4.12(d) show that there is a very strong (R^2 = 0.874) positive logarithmic correlation between S/N response for bean grain damage and mass of threshing cylinder. Note that the S/N response for bean grain damage increased from -23.0 to -19.1 with increase in mass of threshing cylinder from 2 to 10 kg (which was taken to be optimal). This is because mass is a factor of the impact and rubbing force that can cause bean grain damage. However, keeping peripheral speed constant, mass of the threshing cylinder has insignificant effect on grain damage.

The results in Figure 4.12(e) depict that there is a strong (R^2 = 0.664) positive polynomial correlation between S/N response for bean grain damage and moisture content. It was noted that S/N response for bean grain damage increased from -23.6 to -12.8 as grain moisture content increased with an optimal value occurring at 22.5% (w.b) moisture content. During threshing, the bean grains are detached from the pods by a combination of stripping, rubbing, and impact action through the application of tensile, compressive, bending, and twisting forces (Ndirika, 2006). However, this is not effective at extremely high moisture content. Finally, Figure 4.12(f) show that there is a very strong (R^2 = 0.999) positive logarithmic correlation between S/N for bean grain damage and linear concave width. As linear concave width increases from 0.2 to 1.0 m, S/N response for bean grain damage increases from -31.5 to -13.5. This could be because of the increased dwell time of threshed grains in the drum that caused increased separation efficiency. The optimum linear concave width for the thresher was 1 m based on Equation 3.49.

Figure 4.13 presents signal to noise ratio response relationships for threshing efficiency for various thresher design and bean parameters. Optimization criteria for threshing efficiency was to achieve maximum efficiency toward 100% and therefore, considering Equation 3.49, the higher S/N ratio represents the best performance. The results in Figure 4.13(a) show that there is a very strong (R^2 = 0.98) positive logarithmic correlation between S/N for threshing efficiency and peripheral speed of pegs. The S/N response for threshing efficiency increased from 33.4 to 39.1 as peg peripheral speed increased from 1.88 to 5.65 m/s. Using the concept of the higher S/N ratio corresponds to an optimal level, 5.65 m/s peg peripheral was the optimal threshing efficiency. This is true because at high speeds, the application of stripping, rubbing, and impact action that causes threshing is high at the highest peripheral speed. (Osueke, 2011).

On the other hand, Figure 4.13(b) indicates that there was a weak (R^2 = 0.591) polynomial correlation between S/N ratio for threshing efficiency and bulk density of unthreshed beans. It is noted that S/N ratio for threshing efficiency decreased to a minimum then thereafter it increased as bulk density increased. The S/N range of threshing efficiency as affected by bulk density is (36-37.8), an indication of the insignificant effect of the bulk density.

Further, Figure 4.13(c) shows that there was a very strong (R^2 = 0. 963) negative logarithmic correlation between S/N ratio for threshing efficiency and feed rate. It was noted that S/N ratio for threshing efficiency decreased from 38.4 to 34.5 as feed rate increased from 0.01 to 0.05 kg/s. This could be explained by the fact that there was enough dwell time available for the fewer pods to interact with the pegs in motion within the threshing drum during low feed rates. Therefore, feed rate of 0.01 kg/s resulted to optimal threshing efficiency. The results in Figure 4.13(d) show that there is a very strong (R^2 = 0.925) positive logarithmic correlation between S/N for threshing efficiency and linear concave width. S/N for threshing efficiency increased from 33.0 to 38.3 with increase in linear concave width from 0.2 to 1.0 m.



(a) (b)

(c) (d)

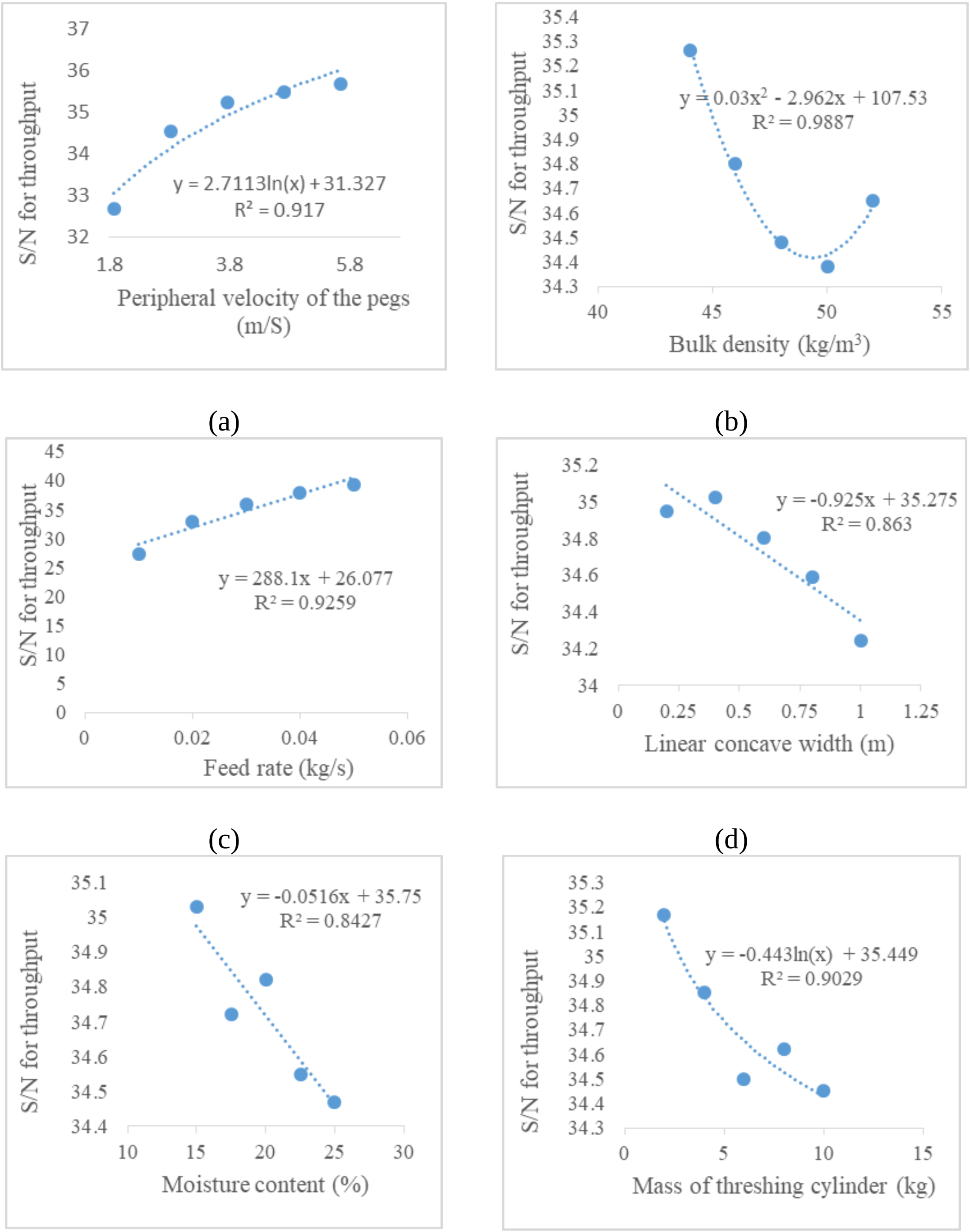
(e) (f)

Figure 4.13: Signal to noise ratio response for threshing efficiency for various thresher design and bean parameters.

Further, the results in Figure 4.13(e) show that there is a strong (R^2 = 0.964) polynomial correlation between S/N for threshing efficiency and moisture content.

Moisture content of 15% for unthreshed common beans yielded the optimal threshing efficiency based on the higher S/N ratio. This is because common beans at moisture content less than 20% do not require much impact force for threshing. A little impact force by the pegs in motion will break common beans pods that results to increased threshing efficiency (Fu *et al*., 2018). Finally, the results in Figure 4.13(f) show that there was a very weak (R^2 = 0.045) polynomial correlation between S/N ratio for threshing efficiency and mass of threshing cylinder. The optimal mass of threshing cylinder that would results to the best threshing efficiency was 8 kg.

Figure 4.14 presents signal to noise ratio response relations for throughput capacity for various thresher design and bean parameters. Optimization criteria for throughput capacity was to achieve the highest output capacity possible and therefore, considering Equation 3.49 or the best line of fit, the higher S/N ratio represented the best performance. The results in Figure 4.14(a) show that there is a very strong (R^2 = 0.917) positive logarithmic correlation between S/N for throughput capacity and peripheral speed of pegs. Increase in peripheral speed of pegs from 1.88 to 5.65 m/s increased S/N ratio for throughput capacity from 32.7 to 35.7, respectively. As a result, dwell time of unthreshed beans in the drum decreased due to increased drum speed. Based on the higher value of S/N for throughput capacity, the peripheral speed of pegs of 5.65 m/s was found to be optimum as it results to increased stripping, rubbing, and impact action on the unthreshed pods. It was also observed that there is a very strong (R^2 = 0.989) polynomial correlation between S/N for throughput capacity and bulk density (Figure 4.14(b)). Bulk density of 44 kg/m^3 for unthreshed common beans was found to be optimum as it corresponded to the highest S/N for throughput capacity. This is because low bulk density enhances smooth running of the drum as opposed to high bulk density which causes seizure of the machine due the high power required. This was observed during the operation of the prototype.



(a) (b)

(c) (d)

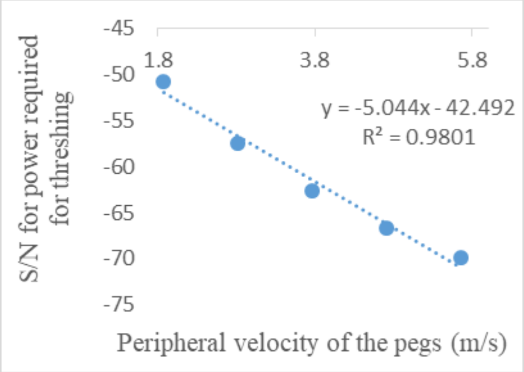
(e) (f)

Figure 4.14: Signal to noise ratio for throughput capacity for various thresher design and bean parameters.

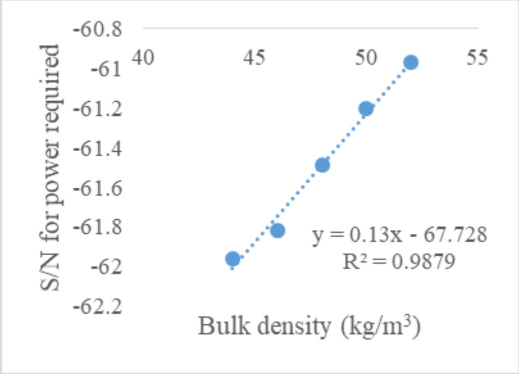
Note also that there is a very strong ($R^2 = 0.926$) linear correlation between S/N for throughput capacity and feed rate (Figure 4.14(c)). Increase in feed rate from 0.01 to 0.05 kg/s increased S/N for throughput capacity from 27.4 to 39.3. This is because increased feed rate reduces dwell time of the bean pods in the drum which in turn increases throughput capacity. The optimal feed rate level was 0.05 kg/s. Further, the results in Figure 4.14(d) show that there is a strong ($R^2 = 0.863$) negative linear correlation between S/N for throughput capacity and linear concave width. The highest S/N for throughput value of 35.1 corresponding to a linear concave width of 0.2 m as per the best line of fit. Concave width of 0.5 m resulted in higher output capacity based on Equation 3.49. It was also observed that there was a very strong ($R^2 = 0.843$) negative linear correlation between S/N for throughput capacity and moisture content (Figure 4.14(e)). Based on these results, a moisture content of 15% (w.b) was found to be optimal as it corresponded to the highest S/N for throughput capacity of 35.0.

Figure 4.15 presents signal to noise ratio response relationship for power requirement for various thresher design and bean parameters. Power required for threshing depends on detachment of the grain from the pod, frictional power, and power required to run the unloaded cylinder (Wamalwa *et al.*, 2021). The optimization criteria were to achieve a low power required for threshing for use of the common beans thresher with multiple energy sources.

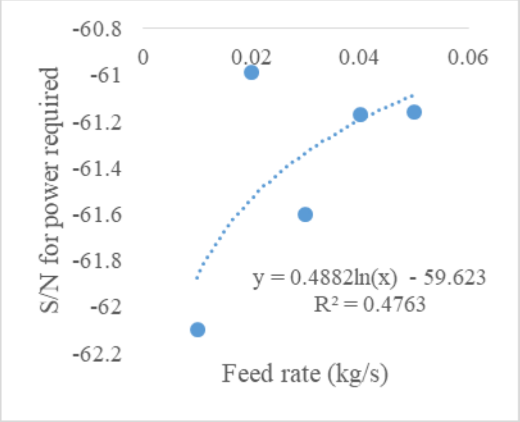
Figure 4.15(a) show that there was a very strong ($R^2 = 0.980$) negative linear correlation between S/N for power requirement and peripheral speed of pegs. The S/N for power requirement decreased from -50.7 to -70.0 with increase in peg peripheral from 1.88 to 5.65 m/s. This is because, increase in peripheral speed of the pegs results to increased power required for threshing that depends on detachment of the grain from the pod, frictional power, and power required to run the unloaded cylinder. The peripheral speed of the pegs that corresponded to the highest S/N ratio was 2.88 m/s which yielded the optimum power required for threshing based on Equation 3.49. This is because there existed a direct proportionality relationship between the pegs' speed and power required for threshing observed during simulation.


S/N for power required for threshing
-45
-50
-55
-60
-65
-70
-75
1.8
3.8
5.8
y = -5.044x - 42.492
R² = 0.9801
Peripheral velocity of the pegs (m/s)

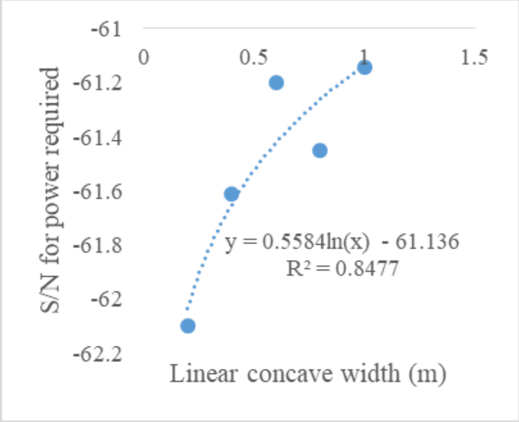
(a)


S/N for power required
-60.8
-61
-61.2
-61.4
-61.6
-61.8
-62
-62.2
40
45
50
55
y = 0.13x - 67.728
R² = 0.9879
Bulk density (kg/m³)

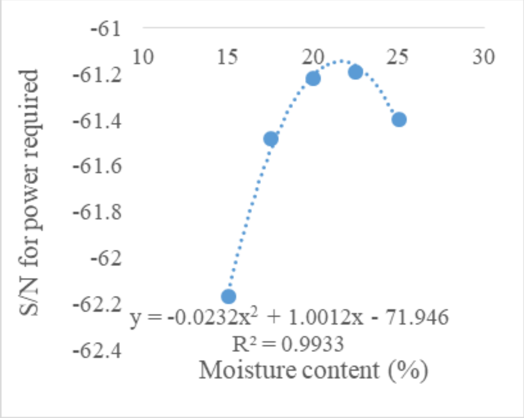
(b)


S/N for power required
-60.8
-61
-61.2
-61.4
-61.6
-61.8
-62
-62.2
0
0.02
0.04
0.06
y = 0.4882ln(x) - 59.623
R² = 0.4763
Feed rate (kg/s)

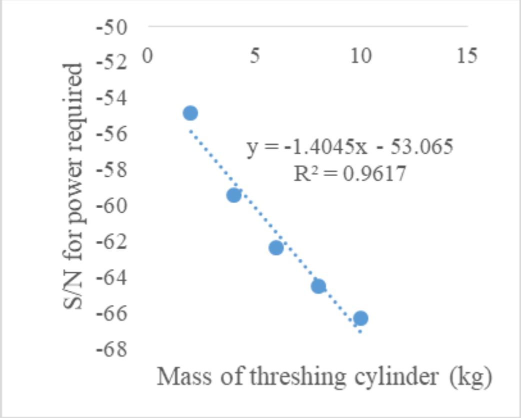
(c)


S/N for power required
-61
-61.2
-61.4
-61.6
-61.8
-62
-62.2
0
0.5
1
1.5
y = 0.5584ln(x) - 61.136
R² = 0.8477
Linear concave width (m)

(d)


S/N for power required
-61
-61.2
-61.4
-61.6
-61.8
-62
-62.2
-62.4
10
15
20
25
30
y = -0.0232x² + 1.0012x - 71.946
R² = 0.9933
Moisture content (%)

(e)


S/N for power required
-50
-52
-54
-56
-58
-60
-62
-64
-66
-68
0
5
10
15
y = -1.4045x - 53.065
R² = 0.9617
Mass of threshing cylinder (kg)

(f)

Figure 4.15: Signal to noise ratio for power requirement for threshing for various thresher design and bean parameters.

On the other hand, Figure 4.15(b) shows that there was a very strong (R^2 = 0.988) linear correlation between S/N for power requirement and bulk density of unthreshed beans. Increase in bulk density from 44 to 52 kg/m^3 slightly increased S/N for power requirement from -62.0 to -61.0. The optimum bulk density to achieve minimum power for threshing was 42 kg/m^3. This is because power required to detach the grains from the pods and to overcome friction decreases with decrease in bulk density. In addition, the results in Figure 4.15(c) show that there is a weak (R^2 = 0.476) positive logarithmic correlation between S/N for power requirement and feed rate. The higher the feed rate the higher power required to bean pod detachment and to overcome frictional forces. A 0.02 kg/s was found to be optimal feed rate.

The results in Figure 4.15(d) show that there is a very strong (R^2 = 0.848) positive logarithmic correlation between S/N for power requirement and linear concave width. This because power required to run the unloaded cylinder increases with increase in concave length, thus increasing the total power. The optimum linear concave length was 1 m-based Equation 3.49. The results in Figure 4.15(e), on the other hand, show that there is a very strong (R^2 = 0.993) polynomial correlation between S/N for power requirement and moisture content. The optimal value for moisture content was 20% based on Equation 3.49. Finally, Figure 4.15(f) shows that there was a very strong (R^2 = 0.962) negative linear correlation between S/N for power requirement and mass of threshing cylinder. The optimum value for mass of the threshing cylinder that resulted in minimum power required for threshing was 2 kg.

The factor level combination that resulted in the optimum performance of the common beans thresher are shown in Table 4.5. The target was to minimize mechanical grain damage and power required for threshing and maximize threshing efficiency as well as throughput capacity. The results in Table 4.5 show that optimum grain damage would be obtained at a factor combination of 1.88 m/s peripheral velocity of the pegs, 52 kg/m^3 bulk density, 0.01 kg/s feed rate, 1 m linear concave width, 22.5% moisture content (w.b), and 10 kg mass of the threshing cylinder. Optimum threshing efficiency would require pegs speed of 5.65 m/s, unthreshed common beans bulk density of 44 kg/m^3, feed rate of 0.01 kg/s, 1 m linear concave width, unthreshed bean moisture content of 15%, and 8 kg mass of the threshing cylinder.

Table 4.5: Factor level combination for optimum performance of common beans thresher

Thresher performance outputs	**Optimum common beans and machine factor combinations**					
	Peripheral speed of pegs (m/s)	**Bulk density (kg/m^3)**	**Feed rate (kg/s)**	**Linear concave width (m)**	**Moisture content (%)**	**Mass of threshing cylinder (kg)**
Grain damage	1.88	52	0.01	1.0	22.5	10
Threshing efficiency	5.65	52	0.01	1.0	15	8
Throughput capacity	5.65	44	0.05	0.4	15	2
Power requirement	1.88	50	0.02	0.6	15	2
Mean optimum combination	3.765	49.5	0.023	0.75	17	5.5

In the case of throughput capacity, the optimum output would need a pegs speed of 5.65 m/s, unthreshed common bean bulk density of 44 kg/m^3, feed rate of 0.05 kg/s, linear concave width of 0.4 m, 15 % moisture content of unthreshed common beans, and 2 kg mass of the threshing cylinder. Finally, the optimum power required for threshing would be obtained by pegs` peripheral speed of 1.88 m/s, unthreshed common bean bulk density of 50 kg/m^3, 0.02 kg/s feed rate, 0.6 m linear concave length, 15 % unthreshed common bean moisture content, and 2 kg mass of the threshing cylinder. However, considering all the outputs of grain damage, threshing efficiency, throughput capacity and power requirement, the mean optimum combination was pegs speed of 3.765 m/s, unthreshed common bean bulk density of 49.5 kg/m^3, feed rate of 0.023 kg/s, linear concave width of 0.75 m, 17 % moisture content of unthreshed common beans, and 5.5 kg mass of the threshing cylinder

4.2.2 Analysis of variance

Tables 4.6 to 4.9 show the results of pooled ANOVA for the four performance outputs (i.e., grain damage, threshing efficiency, throughput capacity and power requirement). The F-ratios were obtained at a 95% level of confidence. In addition, the percentage contribution of each parameter was also calculated. Peripheral speed of the pegs was found to be the most significant factor that contributes to maximum mechanical grain damage (Table 4.6). The contribution of the factors in declining order were peripheral speed (37.5%), feed rate (37.1%), linear concave width (22.2%), unthreshed common moisture content (7.4%), the mass of threshing cylinder (7.4%), and bulk density (2.1%). These results were dissimilar to that of Wangette *et al*., (2015) working on influence of groundnut sheller and machine characteristic on motorised sheller performance using Taguchi method. The results showed that kernel mechanical damage was mostly influenced by ground nut variety (36.56%) and moisture content (31.02%). This was expected because variety of the common beans was not within the scope of this study.

Table 4.6: ANOVA for bean damage

Source of variation	Degrees of freedom (DOF)	Sum of square (SS)	Mean sum of squares	F-Ratio	F-tabulated	Factor % contribution
Total	24	4623.2				
Peripheral speed	4	1735.9	434.0	8.3	2.9	37.5
Bulk density of beans	4	98.9	24.7	0.5	2.9	2.1

Feed rate	4	1715.9	429.0	8.2	2.9	37.1
Linear concave width	4	1025.9	256.5	4.9	2.9	22.2
Moisture content	4	342.5	85.6	1.6	2.9	7.4
Mass of cylinder	4	342.5	85.6	1.6	2.9	7.4
Error	19	991.6	52.2			

Table 4.7 shows analysis of variance for threshing efficiency with the percentage contribution of each input variable. The results show that peripheral speed, feed rate and concave width were the most significant factors that contributed to threshing efficiency. This is true because the peripheral speed of pegs and feed rate result in stripping, rubbing, and impact action through the application of tensile, compressive, bending, and twisting forces that yield optimum threshing efficiency (Dange *et al.*, 2021). Furthermore, the longer the linear concave length the longer will be dwell time of unthreshed pods in the threshing drum which results in improved threshing efficiency. The contribution of the factors in a descending order were concave width (35.9%), peripheral velocity (33.6%), feed rate (17.7%), mass of threshing cylinder (4.9%), bulk density (4.4%) and unthreshed common bean moisture content (3.6%).

Table 4.7: ANOVA for threshing efficiency

Source of variation	**Degrees of freedom (DOF)**	**Sum of squares (SS)**	**Mean sum of squares**	**F-ratio**	**F-tabulated**	**Factor % contribution**
Total	24	277.0				
Peripheral speed	4	93.0	23.2	8.0	2.9	33.6
Bulk density of beans	4	12.1	3.0	1.0	2.9	4.4
Feed rate	4	49.0	12.3	4.2	2.9	17.7
Linear concave width	4	99.4	24.8	8.5	2.9	35.9
Moisture content	4	10.0	2.5	0.9	2.9	3.6

Mass of cylinder	4	13.7	3.4	1.2	2.9	4.9
Error	19	55.4	2.9			

When analysis of variance was conducted for throughput capacity, the feed rate was found to be the only significant factor contributing to 92.4% for maximum output capacity (see Table 4.8).

Table 4.8: ANOVA for throughput capacity

Source of variation	**Degrees of freedom (DOF)**	**Sum of squares (SS)**	**Mean sum of squares**	**F-ratio**	**F tabulated**	**Factor % contribution**
Total	24	485.0				
Peripheral speed	4	30.3	7.6	1.5	2.9	6.2
Bulk density of beans	4	2.4	0.6	0.1	2.9	0.5
Feed rate	4	448.2	112.1	21.9	2.9	92.4
Linear concave width	4	2.0	0.5	0.1	2.9	0.4
Moisture content	4	1.0	0.2	0.0	2.9	0.2
Mass of cylinder	4	1.8	0.4	0.1	2.9	0.4
Error	19	97.1	5.1	1.0		

This implies that throughput capacity is directly proportional to feed rate because, like energy, mass is a conserved property, it cannot be created nor destroyed. The thresher acts like control volume. Therefore, the threshed common beans are the amount of mass flowing through the control volume per unit time known as throughput capacity. Peripheral speed had a contribution effect of 6.2% on throughput capacity which was statistically not significant. This is because if the pegs are in motion and there is no feeding then the mass flow rate is equal to zero.

An optimum common bean thresher requires minimum power for threshing based on other relevant outputs. Table 4.9 indicates the analysis of variance for power required for threshing. Peripheral speed was the most significant contributing at 73.2% followed by the mass of the threshing cylinder at 26.0%. This could be attributed to the fact that total power required for threshing is the total of power required to detach the beans grain from the pods, power needed to overcome frictional forces, and power required to turn the mass of unloaded cylinder.

Table 4.9: ANOVA for power required for threshing

Source of variation	Degrees of freedom (DOF)	Sum of squares (SS)	Mean sum of squares	F-ratio	F-tabulated	Factor % contribution
Total	24	1577.0				
Peripheral speed	4	1154.2	288.5	17.37	2.9	73.19
Bulk density of beans	4	3.4	0.9	0.05	2.9	0.22
Feed rate	4	4.0	1.0	0.06	2.9	0.26
Linear concave width	4	3.0	0.7	0.04	2.9	0.19
Moisture content	4	3.2	0.8	0.05	2.9	0.20
Mass of cylinder	4	410.2	102.6	6.17	2.9	26.01
Error	19	315.6	16.6			

4.2.3 Confirmation test

Table 4.10 shows results of confirmed actual optimum outputs from experiments. The expected value of the outputs at the optimum condition was calculated by adding the average performance to the contribution of each parameter at the optimum level. The expected performance outputs based on Equation 3.50 were grain damage (0.0003%), threshing efficiency (97.0%), throughput capacity (94.5 kg/h), and power required (207.5W). The projected values were similar to the experimentally confirmed outputs.

Table 4.10: Confirmation of actual optimum outputs

Common beans and machine factor combination						Outputs			
V, m/s	ρ, kg/m^3	Q, kg/s	W, m	β, %	Mc, kg	Gd, %	Te, %	$C_{T,}$ kg/h	$P_{T,}$ W
1.88	52	0.01	1	22.5	10	0.00002*	98.9	22.8	516.5
5.65	52	0.01	1	15	8	3.4	99.5*	90.9	724
5.65	44	0.05	0.4	15	2	3.2	99.0	95.0*	779
1.88	50	0.02	0.6	15	2	0.3	98.7	23.1	207*
3.765	49.5	0.023	0.75	17	5.5	1.73	99.025	57.95	556.6

In the table: V- Pegs peripheral speed; ρ, - Bulk density; Q, - feed rate; W, - Concave length; β, - Moisture content; Mc, Gd, - Grain damage; Te, - Threshing efficiency; $C_{T,}$ - Throughput capacity; $P_{T,}$ - Power required for threshing.

The actual optimum performance outputs based on optimum combination factors using the Taguchi method were grain mechanical damage of 0.00002%, threshing efficiency of 99.5%, the throughput capacity of 95.0 kg/h, and 207 W power required for threshing. However, the optimum mean values for bean grain damage of 1.73%, threshing efficiency of 99%, throughput capacity of 57.95 kg/hr and power requirement of 556.6 W were obtained at 3.765 m/s peripheral speed of pegs, 0.023 kg/s feed rate, 1 m linear concave width, 17.5% moisture content (w.b) and 5.5 kg weight of threshing cylinder. The confirmation experiment shows that the Taguchi method enhanced the thresher performance by optimizing the thresher design and bean parameters. The confirmation test done in this section was used to verify the projected result with actual experimental results. If the optimal combination of parameters and their levels coincidently match with one of the experiments in the orthogonal array, then the confirmatory test was not required.

4.3 Performance of the Developed Optimized Common Beans Thresher

4.3.1 Crop characteristic used for evaluation

The variety of beans used for evaluation was the large red kidney type commonly known as “Nyayo”. Maximum length of the bean straw after harvesting was 0.8 m. This was important in the design of the threshing cylinder diameter to avoid winding of the straw that could cause seizure of the machine during operation. Moisture content of threshed beans was taken as 17% (w.b) based on the optimization input factors. The large red kidney beans had grain straw ratio of 0.99. The measured bulk density of bean crop was 48 kg/m^3.

4.3.2 Performance of thresher for different cylinder rotational speeds

The performance of the developed optimised common bean thresher was evaluated for cylinder rotational speeds of 600, 700, 800, 900 and 1000 rpm which corresponded to peripheral speed of pegs of 2.8, 3.3, 3.8, 4.2 and 4.7 m/s, respectively. These were the operational speeds for the machine. Figure 4.16 shows the threshing efficiency of the developed optimized bean thresher for different cylinder rotational speeds. The results show that threshing efficiency increased from 99.1 to 100% with increased cylinder rotational speed from 600 to 900 rpm. There was increase in threshing efficiency with increase in cylinder rotational speed due increased impact force of the pegs responsible for threshing. At peripheral speeds of pegs above 4.2 to 4.7 m/s, threshing efficiency remained constant towards 100% which was the intended target.

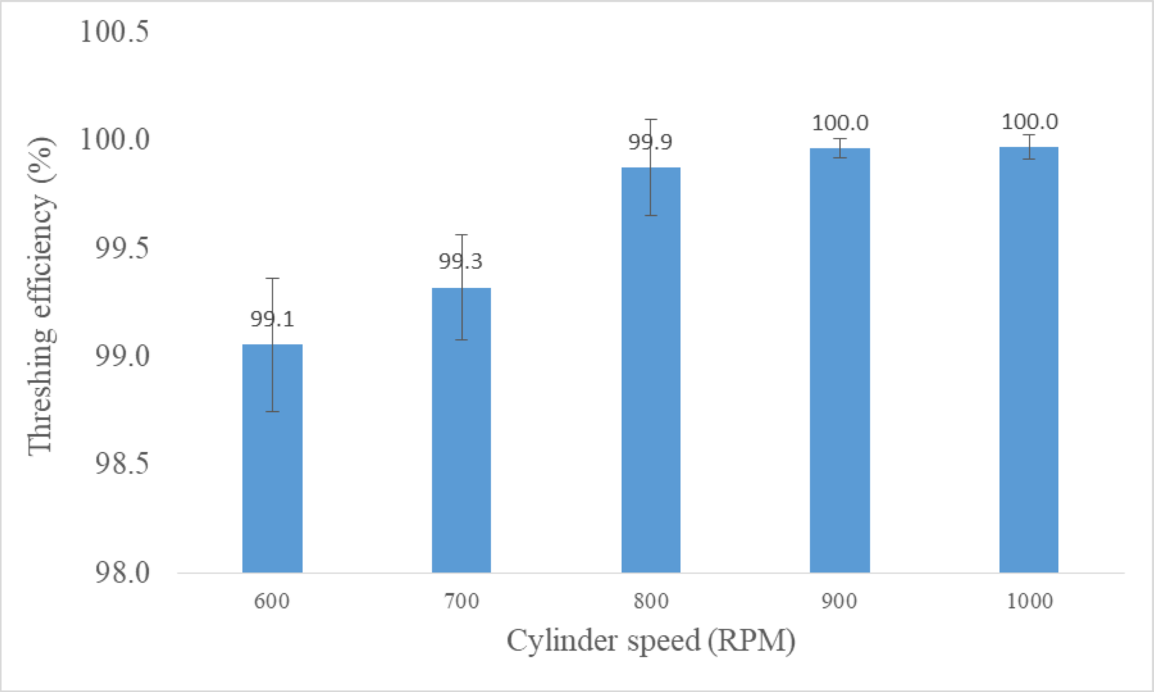


Figure 4.16: Threshing efficiency of the optimised common beans thresher for different cylinder rotational speed.

It was also important to evaluate throughput capacity of the thresher because its key to farmers in relation to time and fuel consumed. Figure 4.17 shows throughput capacity of the developed optimised common beans thresher under different cylinder rotational speeds. Throughput capacity increased from 41.4 to 92.4 kg/hr with increase in cylinder rotational speed from 600 to 1000 rpm. The increase can be attributed to the fact that threshing is enhanced by increased motion of pegs that demand more feeding of unthreshed beans (Sessiz *et al*., 2007).

Traditional threshing of beans by use of sticks yields approximately 15 kg/hr output capacity (Yamba *et al*., 2017). This is output is low compared to any operational speed of the developed thresher. Small scale farmers produce average of five 45 kg bags of beans for sustenance majorly in Kenya (Nyabera, 2015). The developed machine is therefore suitable for small scale farmers because it can thresh a mean of 336 kg of beans for 8 working hours

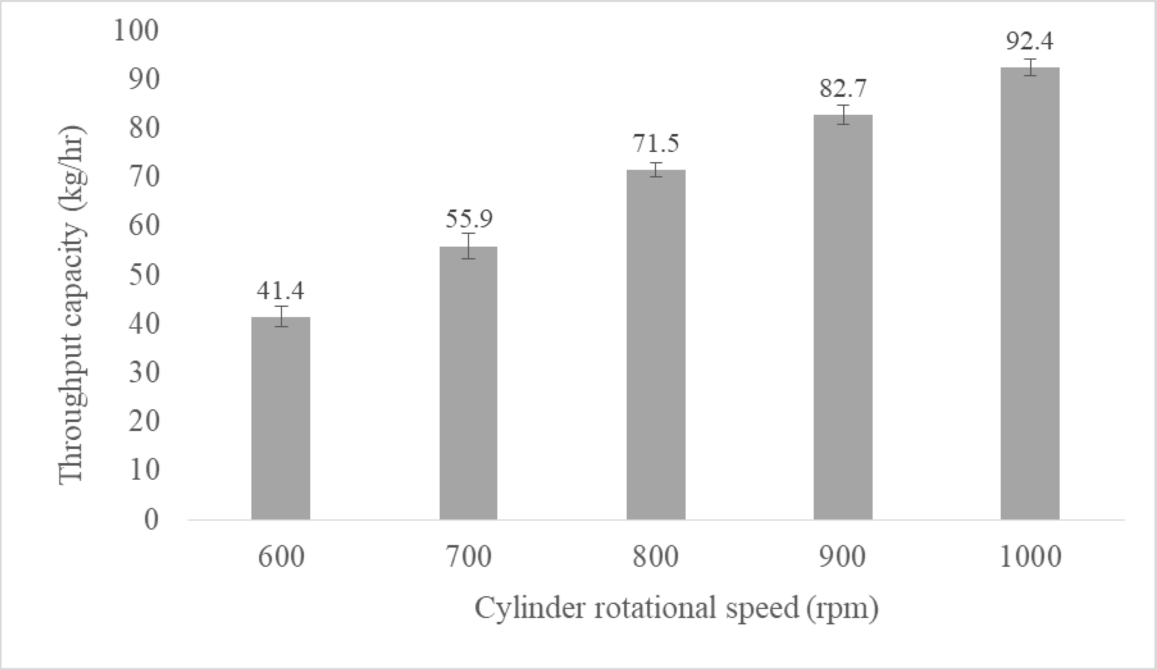


Figure 4.17: Throughput capacity of the developed optimised common beans thresher for different cylinder rotational speeds.

operating at cylinder rotational speed of 800 rpm. At cylinder rotational speed of 1000 rpm, the thresher had a throughput capacity of 92 kg/hr which is commendable to users. However, because of increased grain damage above 3% it is not advisable to use this speed during threshing based on United States Department of Agriculture standard that sets the maximum total damaged grain to be 2%. In the development of threshers' throughput capacity model, it was assumed that the variables of importance were feed rate, grain-straw ratio and separation efficiency. This implies that throughput capacity can also be increased by increased separation efficiency and feed rate.

Grain damage can affect price, feed quality, food product quality, and susceptibility to pest contamination (Banaseer *et al*., 2028). The United States Department of Agriculture (USDA) lists the threshold for broken grain to be anything that will fit through 8/64-inch round-hole sieve for soybeans. The simplest method for assessing grain damage is through visible inspection of the grain; this was employed in this study. Figure 4.18 presents grain mechanical damage under different cylinder rotational speeds of the developed optimised common beans thresher. Mechanical bean grain damage increased from 0 to 3.3% with increase in cylinder rotational speed from 600 to 900 rpm. The increase in grain damage with increase in speed is due to the enhanced impact force generated by thresher as speed increases. There was zero mechanical bean grain damage at cylinder rotational speed of 600 rpm which is good for seed production. The average bean grain mechanical damage was 1.2±1.3% for all the cylinder rotational speeds used.

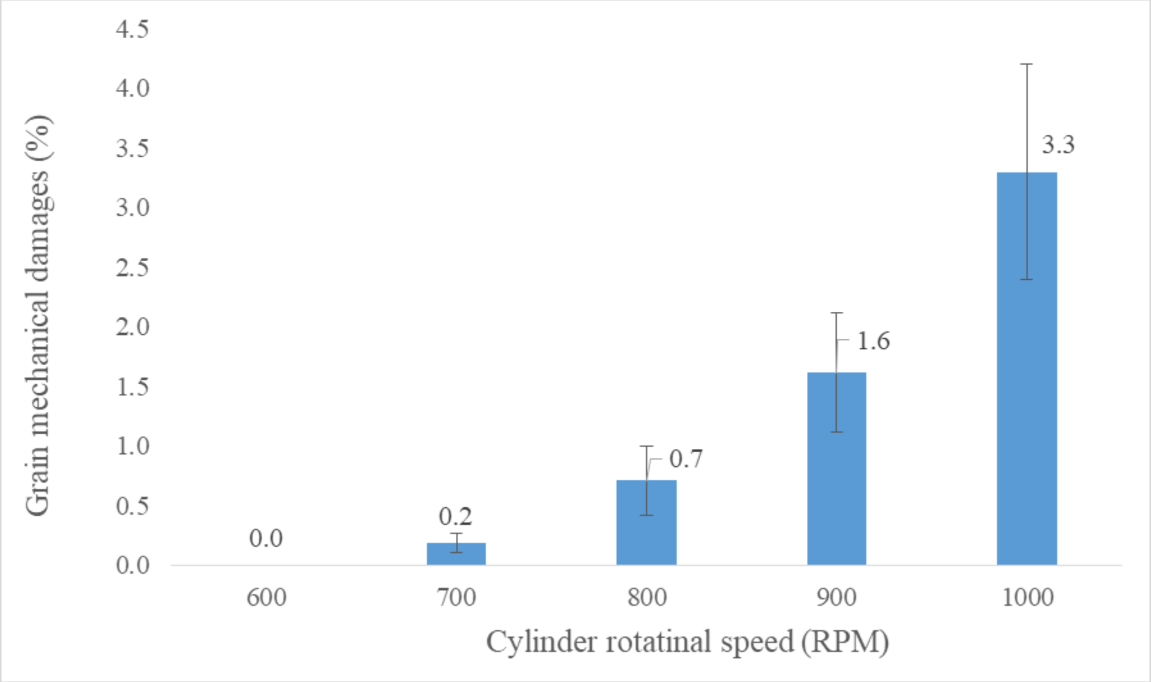


Figure 4.18: Bean grain damage for different cylinder rotational speeds of the developed optimised thresher.

It was observed that rotational speed of 800 rpm resulted to 0.7% mechanical bean grain damage. According to the United States Department of Agriculture, the maximum total damaged grain allowable for grade one grains of soybeans is 2%. Therefore, the developed common beans thresher can operate up to speeds of 900 rpm and still produce grade one grains. At high cylinder rotational speed of 1000 rpm, mechanical bean grain damage increased to 3.3% which may not be suitable for international markets.

It was necessary to test the performance of the developed thresher at different feed rate. The feeding operation was manual. Table 4.11 shows a summary of the performance of the developed optimised common beans thresher at two different feed rates. Feed rate of 0.017 kg/s was an average during normal operation of the machine. The unthreshed beans was fed into the hoper based on demand. However, it was also significant to find out the performance of thresher under continuous feeding. This was achieved by making sure the feed hoper was half full during threshing. An average feed rate of 0.042 kg/s was established under continuous feeding as shown in Table 4.11. The minimum cylinder rotational speed that could operate the thresher during continuous feeding was 800 rpm. As indicated in table, it was clear that increased feed rate resulted to increased throughput capacity.

Table 4.11: Summary of performance of the developed optimised common beans thresher

Feed rate (kg/s)	Cylinder speed (rpm)	Blower speed (m/s)	Threshing efficiency (%)	Throughput capacity (kg/hr)	Bean grain mechanical damages (%)	Cleaning efficiency (%)
0.017	800	6	99.87	71.51	0.71	78.1
	900	8.5	99.69	82.74	1.61	74.0
	1000	10.3	99.90	92.44	3.30	70.2
0.042	800	6	99.69	124.63	0.82	75.1
	900	8.5	99.87	140.68	1.71	72.0
	1000	10.3	99.99	156.31	3.45	68.2

Cleaning of grains was key to a successful common bean thresher. The thresher had a cleaning unit fixed with blower that blew off the chaff and dust which are lighter than grains. Table 4.11 also shows the cleaning efficiency of the developed common beans thresher at different cylinder rotational speeds and feed rate. Cleaning efficiency decreased with increase in cylinder rotational speeds. This could be because at high cylinder rotational speeds, the velocity of air flow increased to beyond the terminal velocity of grains causing the chaff and grains to be blown away.

Finally, energy consumption of the developed optimised common beans thresher was evaluated. The thresher is flexible to use petrol engine or electricity driven motor. The fuel consumed was determined based on the differential volume after each trial. It was established that one litre of petrol was able to thresh 30 kg of beans. This means that with a litre of petrol, a famer can thresh and clean one bag of beans depending on the productivity of the crop.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

1. Mathematical models were developed and coded in python to simulate power requirement, threshing efficiency, grain mechanical damage and throughput capacity. The results show strong to very strong correlations between simulated and actual data for the models (R^2 = 0.993 for power required for threshing, 0.757 for bean mechanical damage, 0.738 for threshing efficiency and 0.985 for throughput capacity). At 5% level of significance, there was no statistical difference between actual and simulated power requirement and throughput capacity. Using residual error analysis, the performances of the models at 10% absolute error were above 77.8%. Finally, the results show that power requirement, bean grain damage, threshing efficiency and throughput capacity increased with increase in pegs peripheral speed from 1.88 m/s to 5.65 m/s for simulated and actual data.
2. In this study the optimization criteria were to minimize bean grain damage and power required for threshing while maximizing threshing efficiency and throughput capacity. The optimum mean values for bean grain damage of 1.73%, threshing efficiency of 99%, throughput capacity of 57.95 kg/hr and power requirement of 556.6 W were obtained at 3.765 m/s peripheral speed of pegs, 0.023 kg/s feed rate, 1 m linear concave width, 17.5% moisture content (w.b) and 5.5 kg weight of threshing cylinder. ANOVA results established that pegs peripheral speed and feed rate were the main contributing factors on bean grain damage, threshing efficiency, and throughput capacity.
3. The developed common beans thresher achieved satisfactory performance since its threshing efficiency was 99% and above for cylinder peripheral speeds greater than 600 rpm. In addition, the throughput capacities were 72 and 125 kg/hr at feed rates of 1 and 2.5 kg/min, respectively, at optimum cylinder rotational speed of 800 rpm. Further, the

thresher attained mechanical bean grain damage of 1.6% and less for cylinder rotational speeds ranging from 900 to 600 rpm. The achieved grain damage is within the acceptable range 2% as recommended by American State Department of Agriculture (Year). Finally, at optimal throughput capacity performance of 92kg/hr the thresher consumed about three (3) litres of petrol and it required two-man hours all these costing Ksh 665. as compared to manual threshing costing Ksh 1500 for three-man days.

5.2 Recommendations

5.21 Recommendations from the study

1. The developed prediction models can successfully be used to simulate design variables for the development of the common bean threshers.
2. The Taguchi optimization technique that was employed in this study can be used to optimize similar grain threshers for mass production. This would reduce the cost of production of bean threshers as the method provides a simple, systematic, and efficient procedure for optimizing design and performance parameters.
3. The developed common beans thresher is recommended for use by small-scale farmers as it achieved satisfactory performance in terms of low grain damage, and high threshing efficiency and throughput capacity.

5.22 Recommendations for further research

1. Since the cleaning efficiency attained by the common bean thresher in this study ranged between and 78.1%, values which were found to be low in relation to other grain threshers, it is recommended that further studies be conducted to improve on cleaning efficiency.
2. The prediction performance achieved for the common beans thresher of 77.8% was low since it was based on 10% residual error interval instead of 5%, a criterion that is used for most agricultural systems. Hence need for further improvements of the thresher.

4. Feeding operation of common beans into the thresher was manual, therefore, automation of the machine operation especially speed control and feed rate need to be incorporated.

REFERENCES

Abdelwahab, N. M. (2006). *The nutritive and functional properties of dry bean flour as affected by Gamma irradiation,* Unpublished PhD dissertation, khartoum: University of khartoum.

Abich, O. (2018). *Optimization of selected parameters of sorghum threshing unit*. Unpublished MSc Thesis, Egerton: Egerton University.

Adekanye, T. A., Osakpamwan, A. B., & Osaivbie, I. E. (2016). Evaluation of a soybean threshing machine for small scale farmers. *Agricultural Engineering International: CIGR Journal*, *18*(2), 426-434.

Adeyemi, O. (2020). Effect of crude oil contaminated soil on *Phaseolus vulgaris* L. *World Journal of Innovative Research*, *8*(2), 28-33.

Agatonovic-Kustrin, S., & Beresford, R. (2000). Basic concepts of artificial neural network (ANN) modeling and its application in pharmaceutical research. *J. Pharm. Biomed. Anal., 22,* 717-727.

Alamy, C (2019). Thresh stocks photos and thresh stocks images. Retrieved from https://www.bing.com/images/

Alarakhia, A. M. (1972). *The development and evaluation op small scale threshing and cleaning mechanisms for grain legumes* Unpublished Phd dissertation, Nairobi: University of Nairobi.

Almirall, A., Bosch, L., del Castillo, R. R., Rivera, A., & Casanas, F. (2010). ‘Croscat’common bean (*Phaseolus vulgaris* L.), a prototypical cultivar within the ‘Tavella Brisa’type. *HortScience*, *45*(3), 432-433.

Ani, K. J., Maxwell, G., & Ecoma, C. S. (2017). Rice production and food security in Nigeria: A synoptic history of the Ikwo brand. *International Journal of Advanced Academic Research, Arts, Humanities & Education*, *3*(4), 1-10.

Anwer, A. M., Elsayed, A., & Zhang, G. (2021). Longitudinal axial flow rice thresher performance optimization using the Taguchi technique. *Agriculture*, *11*(2), 1-14.

Barman, A., Marak, C. M., Barman, R. M., & Sangma, C. S. (2018). Nutraceutical properties of legume seeds and their impact on human health. In *Legume seed nutraceutical research*. IntechOpen.

Beebe, S. E., Rao, I. M., Mukankusi, C. M., & Buruchara, R. A. (2012). *Improving resource use efficiency and reducing risk of common bean production in Africa*, Latin America, and the Caribbean: CIAT.

Befikadu, D. (2018). Postharvest losses in Ethiopia and opportunities for reduction: A review. *International Journal of Sciences: Basic and Applied Research (IJSBAR)*, *38*, 249-262.

Behera, B. K., Dash, S. K., & Das, D. K. (1990). Development and testing of a power-operated wheat thresher. *Agricultural Mechanization in Asia, Africa and Latin America (Japan)*, *21*(4), 15-21.

Benaseer, S., Masilamani, P., Albert, V. A., Govindaraj, M., Selvaraju, P., & Bhaskaran, M. (2018). Impact of harvesting and threshing methods on seed quality-A review. *Agricultural Reviews*, *39*(3), 183-192.

Blair, M. W., Díaz, L. M., Buendía, H. F., & Duque, M. C. (2009). Genetic diversity, seed size associations and population structure of a core collection of common beans (Phaseolus vulgaris L.). *Theoretical and Applied Genetics*, *119*(6), 955-972.

Blesh, J., Hoey, L., Jones, A. D., Friedmann, H., & Perfecto, I. (2019). Development pathways toward “zero hunger”. *World Development*, *118*, 1-14.

Bunyawanichakul, P., Walker, G., Sargison, J., & Doe, P. (2007). Modelling and simulation of paddy grain (rice) drying in a simple pneumatic dryer. *Biosystems engineering*, *96*(3), 335-344.

Chansrakoo, W., & Chuan-Udom, S. (2018). Factors of operation affecting performance of a short axial-flow soybean threshing unit. *Engineering Journal*, *22*(4), 109-120.

Chen, Z., Wassgren, C., & Ambrose, R. K. (2021). Measured damage resistance of corn and wheat kernels to compression, friction, and repeated impacts. *Powder Technology, 380*, 638-648.

Chhabra, S. D. (1975). *Studies on threshing of paddy and wheat by axial flow thresher*. Unpublished PhD thesis, Pantnagar, Nainital: GB Pant University.

CIAT (1995). The Pan-Africa Bean Research Alliance (PABRA): strengthening collaborative bean research in sub-Saharan Africa. 1996-2000. Draft copy. pp. 61. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia

Concave, C. (1969). The effect of selected mechanical threshing parameters on kernel damage and threshability of wheat. *Canadian Agricultural Engineering, 2*(2), 83.

Dange, A. R., Naik, R. K., Dave, A. K., Dhurve, N., & Singh, S. (2021). Design and development of maize cob de-husker cum sheller. Retrieved from https://www.thepharmajournal.com/archives/2021/vol10issue10/PartA/10-10-253-417.pdf

Datta, S., & Mahapatra, S. (2010). Modeling, simulation and parametric optimization of wire EDM process using response surface methodology coupled with grey-Taguchi technique. *International Journal of Engineering, Science and Technology*, *2*(5), 162-183.

De Almeida Costa, G. E., da Silva Queiroz-Monici, K., Reis, S. M. P. M., & de Oliveira, A. C. (2006). Chemical composition, dietary fibre and resistant starch contents of raw and cooked pea, common bean, chickpea and lentil legumes. *Food Chemistry, 94*(3), 327-330.

De Groote, H., Marangu, C., & Gitonga, Z. M. (2020). Evolution of agricultural mechanization in Kenya. *An evolving paradigm of agricultural mechanization development: How much can Africa learn from Asia?* Washington DC: Intl Food Policy Rest Inst. https://doi.org/10.2499/9780896293809.

Deckler, H. C. (1997). *Adjustment mechanism for row unit*, Washington, DC: U.S. Patent and Trademark Office.

Delgado, L., Schuster, M., & Torero, M. (2017). Reality of food losses: A new measurement methodology. Retrieved from https://mpra.ub.uni-muenchen.de/80378/ MPRA Paper No. 80378, posted 28 Jul 2017 15:57 UTC

Derese, K. G. (2014). *Design and development of groundnut sheller*. Unpublished MSc Thesis, Haramaya: Haramaya University.

Desta, K., & Mishra, T. N. (1990). Development and performance evaluation of a sorghum thresher. *AMA, Agricultural Mechanization in Asia, Africa and Latin America*, *21*(3), 33-37.

Dhananchezhiyan, P., Parveen, S., Pandian, S., Karpoora, N., & Rangasamy, K. (2015). Development and comparative study of cast iron rasp bar and nylon rasp bar threshing cylinders for paddy threshing. *Agricultural Engineering Journal, 4,* 45 – 54.

Dion, F. A. (1952). *Auxiliary grain separator for combines*, Washington, DC: U.S. Patent and Trademark Office.

Duke, J. (2012). *Handbook of legumes of world economic importance*. New York: Springer Science & Business Media.

Dysarz, T. (2018). Application of python scripting techniques for control and automation of HEC-RAS simulations. *Water*, *10*(10), 13-82.

El-Behery, A. (1995). *Development and evaluation of multi-crop thresher.* Unpublished PhD thesis, Moshtohor:Moshtohor University.

Enaburekhan, J. S. O. (1994). *Mathematical and optimization modeling of the threshing process in a stationery grain thresher*. Unpublished PhD Thesis Zaria, Nigeria: Ahmadu Bello University.

Food and Agriculture Organization (FAO) (2008). "Productions, crops." *Retrieved September* 15 (2008): 2010, FAOSTAT Retreieved from http://faostat.fao.org/default.aspx

Fu, J., Chen, Z., Han, L., & Ren, L. (2018). Review of grain threshing theory and technology. *International Journal of Agricultural and Biological Engineering*, *11*(3), 12-20.

Gathage, J. W. (2018). *Prospects of fungal endophytes in the control of Liriomyza leafminer flies (Diptera: Agromyzidae) in common bean Phaseolus vulgaris Linnaeus (Fabales: Fabaceae) under field conditions* Unpublished PhD dissertation, Juja: Jomo Kenyatta University of Agriculture and Technology).

Gbabo, A., Gana, I. M., & Amoto, M. S. (2013). Design, fabrication and testing of a millet thresher. *Net Journal of Agricultural Science, 1*(4), 100-106.

Gbabo, A., Gana, I. M., & Amoto, M. S. (2013). Design, fabrication and testing of a millet thresher. *Net Journal of Agricultural Science*, *1*(4), 100-106.

Gentry, H. S. (1969). Origin of the common bean, Phaseolus vulgaris. *Economic Botany*, *23*(1), 55-69.

Goss. J.R., R. A Kepner and L.G Jones. (1958). Perfomance characteristic of grain combine in barley. *Tansaction of the ASAE, 39*(11), 679-702

Gregory, J. M. (1988). Combine model for grain threshing. *Mathematical and Computer Modelling*, *11,* 506-509.

Gupta, J. K. & Khurmi, R. S, (2005). *Machine design*. (14th Ed.) S Ram Nagar, New Delhi: Chand & Company Ltd.,.

Hamdy, M. Y. (1965). *Theoretical analysis of centrifugal threshing and separation.* Ohio: The Ohio State University.

Harrison, H. P. (1969). The effect of selected mechanical threshing parameters on kernel damage. *Canadian Agricultural Engineering*, *11*(2), 83-87.

Hart, W. E., Watson, J. P., & Woodruff, D. L. (2011). Pyomo: modeling and solving mathematical programs in Python. *Mathematical Programming Computation*, *3*(3), 219-260.

Hayat, I., Ahmad, A., Masud, T., Ahmed, A., & Bashir, S. (2014). Nutritional and health perspectives of beans (*Phaseolus vulgaris* L.): an overview. *Critical Reviews in Food Science and Nutrition*, *54*(5), 580-592.

Huynh, V. M., Powell, T., & Siddall, J. N. (1982). Threshing and separating process A mathematical model. *Transactions of the ASAE*, *25*(1), 65-73.

Jackson, O.D., Nalugala, R., & Asatsa, S. (2021). Food Production and Food Insecurity: Lessons from Small Holder Farming in Ugunja Sub County, Kenya. *Journal of research innovation and implication ineducation, 5*(3), 38 – 49.

Joshi, N. L. (2006). Harvest and post-harvest practices and losses in arid legumes. *Arid Legumes for Sustainable Agriculture and Trade, 2*(2), 385-388.

Joshi, P. K., Bahl, D. K., & Jha, D. (1981). Direct employment effect of technical change in Uttar Pradesh agriculture. *Indian Journal of Agricultural Economics*, *36*(902-2018-1814), 1

Kamonzo Jedidah, K., Mutisya Daniel, L., Muli Benjamin, K., & Nguluu Simon, N. (2018). Comparative whitefly vector density and bean disease incidence on local and hybrid varieties in semi-arid Kenya. *GSC Biological and Pharmaceutical Sciences*, *5*(3).

Kanali, C. L. (1997). Prediction of axle loads induced by sugarcane transport vehicles using statistical and neural-network models. *Journal of Agricultural Engineering Research*, *68*(3), 207-213.

Karna, S. K., Singh, R. V., & Sahai, R. (2012). Application of Taguchi method in Indian industry. *International Journal of Emerging Technology and Advanced Engineering*, *2*(11), 387-391.

Katungi, E., Farrow, A., Chianu, J., Sperling, L., & Beebe, S. (2009). Common bean in Eastern and Southern Africa: a situation and outlook analysis. *International Centre for Tropical Agriculture*, *61*, 1-44.

Katungi, E., Farrow, A., Mutuoki, T., Gebeyehu, S., Karanja, D., Alamayehu, F., & Buruchara, R. (2010). Improving common bean productivity: An Analysis of socioeconomic factors in Ethiopia and Eastern Kenya. *Baseline Report Tropical legumes II. Centro Internacional de Agricultura Tropical-CIAT. Cali, Colombia*, *126*.

Katungi, E., Sperling, L., Karanja, D., & Beebe, S. (2011). Relative importance of common bean attributes and variety demand in the drought areas of Kenya. *Journal of Development and Agricultural Economics*, *3*(8), 411-422.

Katungi, E., Wozemba, D., & Rubyogo, J. (2011). A cost benefit analysisof farmer based seed production for common bean in Kenya. *African Crop Science Journal*, *19*(4), 409-415.

Kiaya, V. (2014). Post-harvest losses and strategies to reduce them. *Technical Paper on Postharvest Losses, Action Contre la Faim (ACF)*, *25*, 1-25.

Kiplagat, J., Wang, R., & Li, T. (2011). Renewable energy in Kenya: Resource potential and status of exploitation. *Renewable and Sustainable Energy Reviews, 15*(6), 2960-2973.

Kiptoo, G. J., Kinyua, M., Kiplagat, O., Wanjala, F. M. E., Kiptoo, J. J., Cheboi, J. J., & Ngurwe, J. K. (2016). Evaluation of common bean (*Phaseolus vulgaris* L.) varieties for resistance to bean stem maggot (Ophiomyia spp.) in Kenya. *Journal of Experimental Agriculture International*, *12*(3), 1-7.

Kituu, G. M., Shitanda, D., Kanali, C. L., Mailutha, J. T., Njoroge, C. K., Wainaina, J. K., & Silayo, V. K. (2010). Thin layer drying model for simulating the drying of Tilapia fish (*Oreochromis niloticus*) in a solar tunnel dryer. *Journal of Food Engineering, 98*(3), 325-331.

Klein, L., & Harmond, J. (1966). Effect of varying cylinder speed and clearance on threshing cylinders in combining crimson clover. *Transactions of the ASAE, 9*(4), 499-500.

Krishnan, P., Evans, T. A., & Pill, W. G. (1994). Threshing cylinder speed affects germination of amaranths cruentus L. seeds. *HortScience, 29*(6), 652-654.

Kumar, D. (2003). *design, development and evaluation of experimental plot seed thresher.* New Delhi: Indira Gandhi Krishi Vishwavidyalaya, Raipur.

Kumar, D., Kumar, A., Khan, K., & Singh, U. V. (2016). Performance evaluation of power thresher for wheat crop. *Int. J. Adv. Sci. Res, 6,* 195-204.

Lalor, W., & Buchele, W. F. (1963). Designing and testing of a threshing cone. *Transactions of the ASAE, 6*(2), 73.

Law, A. M., Kelton, W. D., & Kelton, W. D. (2000). *Simulation modeling and analysis.* (Vol. 3). New York: McGraw-Hill.

Leterme, P. (2002). Recommendations by health organizations for pulse consumption. *British Journal of Nutrition, 88*(S3), 239-242.

Lin, S.-N. (1977). *Effect of grain moisture and machine adjustments on grain sorghum threshability and seed damage.* Kansas: Kansas State University.

Lohan, S. K., Jakhar, S. S., & Kharb, R. P. S. (2007). Comparative Performance of different threshing mechanisms on Pigeonpea seed quality. *Journal of Agricultural Engineering*, *44*(3), 51-54.

Mabea, G., Macatangay, R. E., & Mutua, J. (2018). 60 Years electricity reform progress in Kenya. Retrieved from https://dx.doi.org/10.2139/ssrn.3100565

Maertens, K., & De Baerdemaeker, J. (2003). Flow rate based prediction of threshing process in combine harvesters. *Applied Engineering in Agriculture, 19*(4), 383.

Maingi, J. M., Shisanya, C. A., Gitonga, N. M., & Hornetz, B. (2001). Nitrogen fixation by common bean (Phaseolus vulgaris L.) in pure and mixed stands in semi-arid south-east Kenya. *European Journal of Agronomy*, *14*(1), 1-12.

Manandhar, A., Milindi, P., & Shah, A. (2018). An overview of the post-harvest grain storage practices of smallholder farmers in developing countries. *Agriculture, 8*(4), 57.

McDonald, M. F., & Copeland, L. O. (2012). *Seed production: principles and practices*. New York: Springer Science & Business Media.

Mesquita, C., & Hanna, M. (1993). Soybean threshing mechanics: I. Frictional rubbing by flat belts. *Transactions of the ASAE, 36*(2), 275-279.

Miu, P. I., & Kutzbach, H.-D. (2008a). Modeling and simulation of grain threshing and separation in axial threshing units: Part II. Application to tangential feeding. *Computers and Electronics in Agriculture, 60*(1), 105-109.

Miu, P. I., & Kutzbach, H.-D. (2008b). Modeling and simulation of grain threshing and separation in threshing units—Part I. *Computers and Electronics in Agriculture*, *60*(1), 96-104.

Montoya, C. A., Lallès, J.-P., Beebe, S., & Leterme, P. (2010). Phaseolin diversity as a possible strategy to improve the nutritional value of common beans (*Phaseolus vulgaris*). *Food Research International, 43*(2), 443-449.

Mostafa M. M., Nouby M. G., Abd El-Gwwad K. A., Mahmoud K. R. and Abd-El-Tawwab A. M. (2013). Optimization of a new wedge disc brake using Taguchi Approach, *Int. Journal of Engineering Research and Applications, 3*(6), 735-744

Moussa, A. J. (2006). The effect of selected mechanical threshing parameters on threchability of some legume crops. *Journal of Agricultural Economics and Social Sciences*, *31*(7), 4297-4312.

Muasya, R. M. (2001). *Crop physiological analysis of seed quality variation in common bean (Phaseolus vulgaris L.)* Wageningen: Wageningen University.

Mudryj, A. N., Yu, N., & Aukema, H. M. (2014). Nutritional and health benefits of pulses. *Applied Physiology, Nutrition, and Metabolism*, *39*(11), 1197-1204.

Muhumuza, K. A. (2019). *International Funding Mechanisms for Kenya's Big Four: The Case of Food Security* Unpublished PhD dissertation, Nairobi: United States International University-Africa.

Muna, N. H., Muhammed, U. S., El-Okente, A. M., & Isiaka, M. (2016). Development and Validation of Threshing Efficiency Mathematical and

Optimization Model for Spike-Tooth Cereal Threshers. *International Journal of Engineering Research and Development*, *12*(11), 50-60.

Mutai, O. K. (2018). *Effect of seed source and post-harvest handling techniques on seed quality and yield of soybean* Unpublished PhD dissertation, Nairobi:University of Nairobi.

Mutuku, J. M., Wamonje, F. O., Mukeshimana, G., Njuguna, J., Wamalwa, M., Choi, S. K., & Ghimire, S. R. (2018). Metagenomic analysis of plant virus occurrence in common bean (Phaseolus vulgaris) in central Kenya. *Frontiers in Microbiology*, *9*, 29-39.

Mutungi, C., Tungu, J., Amri, J., Gaspar, A., & Abass, A. (2022). Nutritional benefits of improved post-harvest handling practices for maize and common beans in Northern Tanzania: A quantitative farm-level assessment. *Journal of Stored Products Research*, *95*, 101-118.

Mwangi, J. K., Mutungi, C. M., Midingoyi, S. K. G., Faraj, A. K., & Affognon, H. D. (2017). An assessment of the magnitudes and factors associated with post-harvest losses in off-farm grain stores in Kenya. *Journal of Stored Products Research*, *73*, 7-20.

Nalado, D. D. (2015). *Development of modeling shelling parameters and optimization of the performance of a stationary IAR maize dehusker sheller*. Unpublished PhD Thesis., Zaria: Ahmadu Bello University.

Ndirika, V. (1997). *Modeling the performance of selected stationary grain threshers.* Unpublished Ph. D Thesis, Zaria:Ahmadu Bello University.

Ndirika, V. (2005). A mathematical model for predicting output capacity of selected stationary grain threshers. *Agricultural Mechanization In Asia Africa and Latin America, 36*(2), 9.

Ndirika, V. (2006). A mathematical model for predicting output capacity of selected stationary spike-tooth grain threshers. *Applied Engineering in Agriculture, 22*(2), 195-200.

Ndirika, V. I. O. (1997). *Modeling the performance of selected stationary grain threshers.* Unpublished PhD Thesis, Zaria: Ahmadu Bello University.

Ndirika, V. I. O. (2003). A simulation of optimum power requirements of selected grain threshers. *Arid Zone Journal of Engineering, Technology and Environment, 3*, 1-11.

Olaoye, J. O., Oni, K. C., & Olaoye, M. M. (2010). Computer applications for selecting operating parameters of stationary grain crop thresher. *International Journal of Agricultural and Biological Engineering, 3*(3), 8-18.

Olaoye, J., Oni, K., & Olaoye, M. (2011). Computer applications for selecting operating parameters in a stationary grain crop thresher. *Journal of Agricultural Technology, 7*(1), 39-56.

Opole, R., Mathenge, P., Auma, E., Van Rheenen, H., & Almekinders, C. (2003). *On-farm seed production practices of common bean (Phaseolus vulgaris L.).* Paper presented at the African Crop Science Conference Proceedings.

Oraibi, A. G., Ahmed, M. H., & Muhamad, W. A. (2015). Investigating the effects of UV radiation and tissue culture techniques on anti-amylase inhibitor activity extracted from white kidney bean (Phaseolus vulgaris L.). *International Journal for Sciences and Technology, 143*(2495), 1-10.

Osueke, C. O. (2011). Simulation and optimization modeling of performance of a cereal thresher. *Int J Eng Technol IJET-IJENS, 11*(3), 143-152.

Osueke, E. C. (2014). O. Study of the influence of crop, machine and operating parameters on performance of cereal threshers. *International Journal of Engineering Research and Development*, *7*(9), 1-9.

Pachico, D. (1989). Trends in world common bean production. *Bean Production Problems in the Tropics, 10*(1), 1-33

Park, C.K. and Ha, J.Y. (2005). A process for optimizing sewing conditions to minimize seam pucker using the Taguchi method. *Textile Research Journal*, 75, 245-252.

Peffers, K., Tuunanen, T., Rothenberger, M. A., & Chatterjee, S. (2007). A design science research methodology for information systems research. *Journal of management information systems*, *24*(3), 45-77.

Pohl, K. (2010). *Requirements engineering: Fundamentals, principles, and techniques*, New York: Springer Publishing Company, Inc.

Qian, Z., Jin, C., & Zhang, D. (2017). Multiple frictional impact dynamics of threshing process between flexible tooth and grain kernel. *Computers and Electronics in Agriculture, 141*, 276-285.

Ramteke, A. S., & Sirohi, N. P. S. (2003). Studies on Design parameters for linseed crop thresher. *Journal of Agricultural Engineering, 40*(2), 39-45.

Rao, S. S. (2019). *Engineering optimization: Theory and practice*. John Wiley & Sons.

Roberts, A., & Arnold, P. (1966). Grain Damage due to Agricultural Machinery Part 1-Harvesting Machines (survey only) and Auger Conveyors.

Rubyogo, J. C., Sperling, L., Nasirumbi, L., & Kasambala, S. (2007). *Developing seed systems with and for the marginalized: case of common beans (Phaseolus vulgaris L.) in East, Central and Southern Africa.* Paper presented at the Proceedings of Farmer First Revisited Conference, Sussex, UK.

Ryan, T. P. (2011). *Statistical methods for quality improvement*. New York: John Wiley & Sons.

Sahu, D. S., Singh, A., & Singh, M. D. (1980). Farm power sources and their utilization in NEH Region.

Sale, N. A. (2015). *Development of an improved IAR sorghum thresher*. Unpublished MSc Thesis, Zaria: Ahmadu Bello University,

Sandhu, K. S., You, F. M., Conner, R. L., Balasubramanian, P. M., & Hou, A. (2018). Genetic analysis and QTL mapping of the seed hardness trait in a black common bean (Phaseolus vulgaris) recombinant inbred line (RIL) population. *Molecular breeding*, *38*(3), 1-13.

Sangakkara, U. (1988). Effect of threshing method, drying temperature and storage condition on microbial deterioration of soybean seeds. *Journal of Applied Seed Production, 6*, 1-5.

Scariot, Maurício Albertoni, Guilherme Tiburski, Francisco Wilson Reichert, Lauri Lourenço Radünz, and Michele Renata Revers Meneguzzo. "Moisture content at harvest and drying temperature on bean seed quality." *Pesquisa Agropecuária Tropical, 47* (2017), 93-101.

Schloesser, C. M. (1998). System for threshing podded produce Washington, DC: U.S. Patent and Trademark Office

Schwartz, H. F., & Corrales, M. A. P. (Eds.). (1989). *Bean production problems in the tropics*. Colombia:CIAT.

Sessiz, A., Koyuncu, T., & Pinar, Y. (2007). Soybean threshing efficiency and power consumption for different concave materials. *Ama, Agricultural Mechanization in Asia, Africa & Latin America, 38*(3), 56-59.

Shandilya, A. (1987). *Effect of grain type and straw type on separation in combines.* Texas: Texas Tech University.

Shimelis, E. A., & Rakshit, S. K. (2005). Proximate composition and physico-chemical properties of improved dry bean (*Phaseolus vulgaris* L.) varieties grown in Ethiopia. *LWT-Food Science and Technology, 38*(4), 331-338.

Simonyan, J., & Yiljep, D. (2008). Investigating grain separation and cleaning efficiency distribution of a conventional stationary rasp-bar sorghum thresher. *Agricultural Engineering International: CIGR Journal, X(2008), 1-13,*

Simonyan, K. J., Yiljep, Y., & Mudiare, O. (2006). Modeling the grain cleaning process of a stationary sorghum thresher. *Agricultural Engineering International: CIGR Journal, VIII,* 1–16

Singh, D., & Vinay, D. (2014). Optimization of machine parameters of Parvatiya Sugam motorized thresher using response surface methodology. *Journal of Applied and Natural Science*, *6*(1), 207-213.

Singh, K. P., Poddar, R. R., Agrawal, K. N., Hota, S., & Singh, M. K. (2015). Development and evaluation of multi millet thresher. *Journal of Applied and Natural Science*, *7*(2), 939-948.

Singh, K., & Bachchan S. (1981). Effect of crop and machine parameters on threshing effectiveness and seed quality of soybean. *Journal of Agricultural Engineering Research, 26*(4), 349-355.

Sinha, J. P. (2009). Studies on machine-crop parameters for chickpea seed crop threshing. *Agricultural Engineering International: CIGR Journal, 6*(2009), 1-9

Sirman, M. B., Owens, E. C., & Whitney, K. A. (2000). Emissions comparison of alternative fuels in an advanced automotive diesel engine. *SAE transactions*, 2166-2176.

Špokas, L., Steponavičius, D., & Petkevičius, S. (2008). Impact of technological parameters of threshing apparatus on grain damage. *Agronomy Research, 6,* 367-376.

Sudajan, S., Salokhe, V. M., & Chusilp, S. (2005). Effect of concave hole size, concave clearance and drum speed on rasp-bar drum performance for threshing sunflower. *Agricultural Mechanization in Asia Africa and Latin America*, *36*(1), 49-57.

Sudajan, S., Salokhe, V., & Triratanasirichai, K. (2002). Power and machinery: effect of type of drum, drum speed and feed rate on sunflower threshing. *Biosystems Engineering, 83*(4), 413-421.

Suleiman, J., & Dangora, N. (2017). Performance evaluation of Deutz-Fahr M1202 combine harvester on rice crop in Kano State-Nigeria. *Journal of Dryland Agriculture, 3*(1), 36-47.

Tefera, T. (2012). Post-harvest losses in African maize in the face of increasing food shortage. *Food Security, 4*(2), 267-277.

Tesfaye, T. and Dibaba, T. (2015). Evaluation and selection of existing machines for rice threshing, *Journal of Multidisciplinary Engineering Science and Technology 2*(7), 1147 – 1150.

Tibagonzeka, J. E., Akumu, G., Kiyimba, F., Atukwase, A., Wambete, J., Bbemba, J., & Muyonga, J. H. (2018). Post-harvest handling practices and losses for legumes and starchy staples in Uganda. *Agricultural Sciences, 9*(1), 141-156.

Uebersax, M. A., Siddiq, M., Cramer, J., & Bales, S. (2022). Harvesting, postharvest handling, distribution, and marketing of dry beans. *Dry Beans and Pulses: Production, Processing, and Nutrition*, 81-104.

Ukatu, A. C. (2006). A modified threshing unit for soya beans. *Biosystems Engineering*, *95*(3), 371-377.

Van Loon, M. P., Deng, N., Grassini, P., Edreira, J. I. R., Wolde-Meskel, E., Baijukya, F., & van Ittersum, M. K. (2018). Prospect for increasing grain legume crop production in East Africa. *European Journal of Agronomy*, *101*, 140-148.

Van Schoonhoven, A., & Voysest, O. (1989). Latin America and their constraints. *Bean Production Problems in the Tropics*, 33- 57

Vas, F.M., & Harrison H. P., (1969). The effect of selected mechanical threshing parameters on kernel damage and threshability of wheat. *Journal of canadian Agricicultural Engineering.*, *11*(2), 83-91.

Vejasit, A., & Salokhe, V. (2004). *Studies on machine-crop parameters of an axial flow thresher for threshing soybean.* Texas: Texas A&M University

Vejasit, A., and V. Salokhe. (2004). Studies on machine-crop parameters of an axial l ow thresher for threshing soybean. *Agric. Eng. Int. GIGR J. Sci. Res. Dev. 6,* 04 004.

Wamalwa, P. W., Kanali, C. L., Ronoh, E. K., & Kituu, G. M. (2021). Simulation of design variables effect on performance of a common beans (*Phaseolus vulgaris* L) portable thresher. *INMATEH-Agricultural Engineering*, *65*(3), 452-464

Wangette, S., Nyaanga Daudi, M., & Njue Musa, R. (2015). Influence of groundnut and machine characteristics on motorised sheller performance. *American Journal of Agriculture and Forestry*, *3*(5), 178-191.

Wolgast, E. H. (1956). *Stone deflecting means for a cylinder and concave type thresher* Washington, DC: U.S. Patent and Trademark Office.

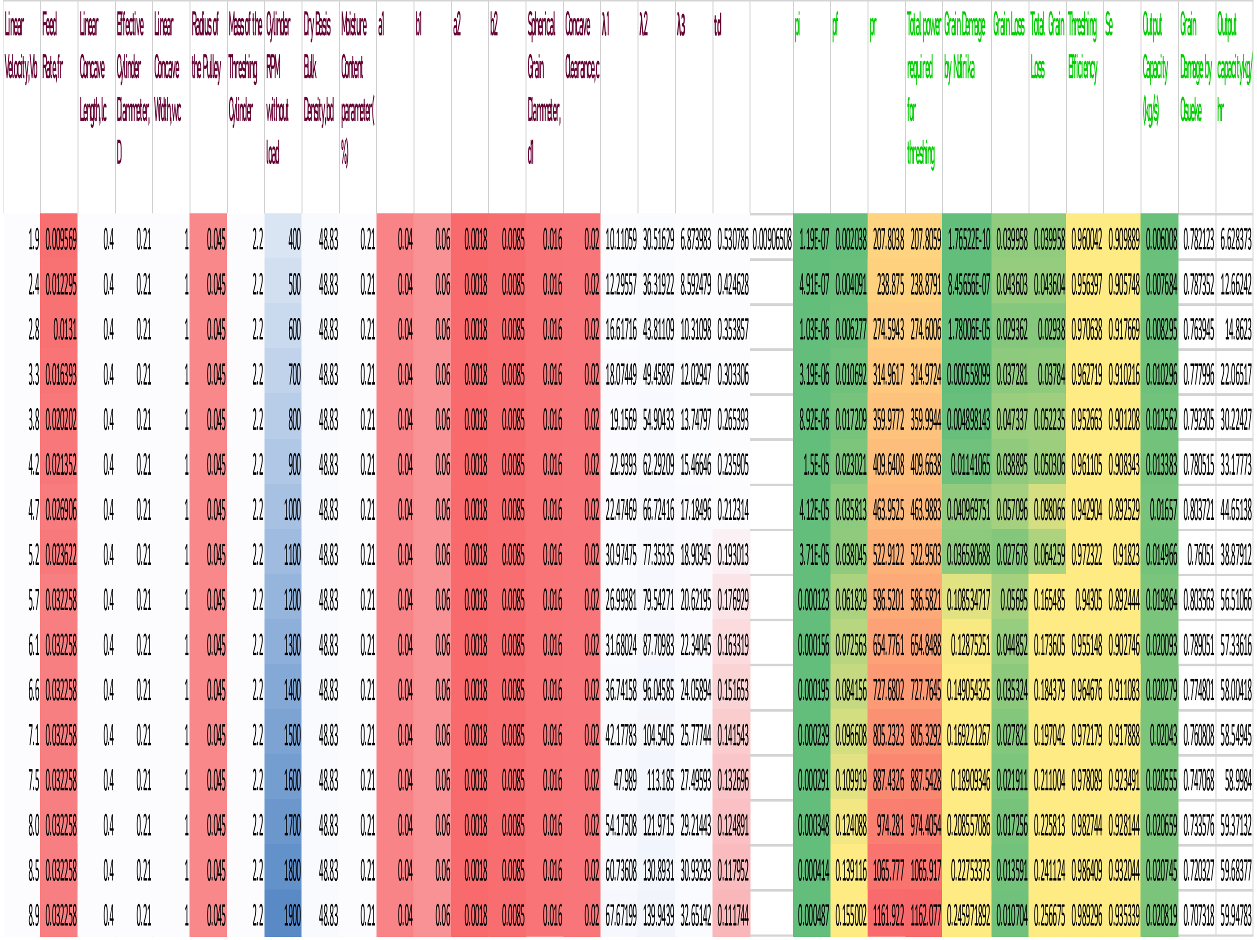
Wortmann, C. S. (1998). *Atlas of common bean (Phaseolus vulgaris L.) production in Africa* (No. 297). CIAT.

Yamba, P., Larson, E. A., Issaka, Z., & Akayeti, A. (2017). Design, Manufacture and Performance Evaluation of a Soybean Paddle Thresher with a Blower. *Life*, *7*-8.

Yu, J., Lam, A. & Li. V. (2015). Evolutionary artificial neural network based on chemical reaction optimization. *Neurocomputing*, *71*(6), 1054-1060.

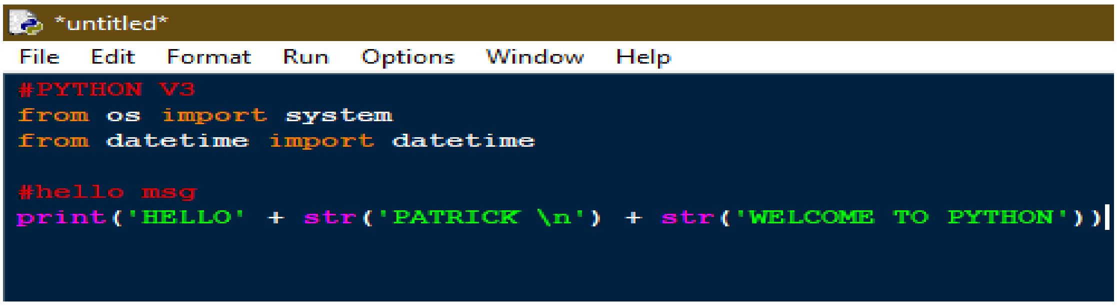
APPENDICES

Appendix I: Computer simulation of design parameters and performance

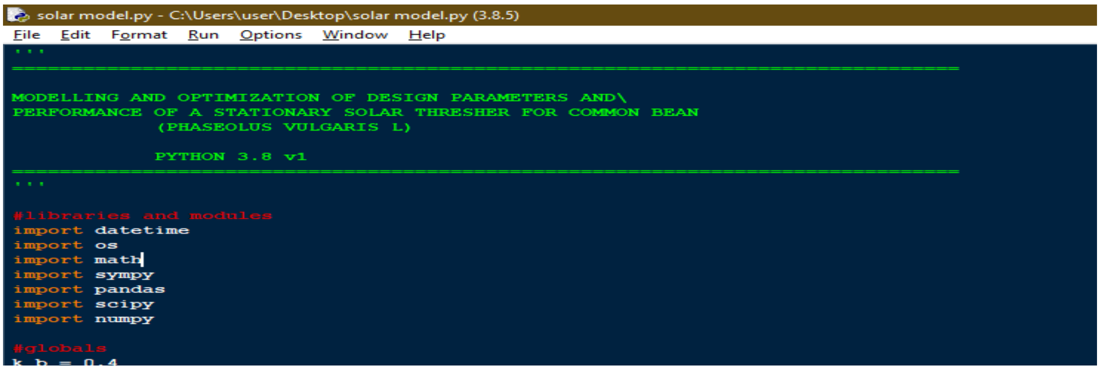


Linear Velocity,Vb	Feed Rate,fr	Linear Concave Length,lc	Effective Cylinder Dammeter, D	Linear Concave Width,wc	Radius of the Pulley	Mass of the Threshing Cylinder	Cylinder RPM without load	Dry Basis Bulk Density,bd	Moisture Content parameter(%)	a1	b1	a2	b2	Spherical Grain Dammeter, d1	Concave Clearance,c	λ1	λ2	λ3	td		pi	pf	pr	Total power required for threshing	Grain Damage by Ndirika	Grain Loss	Total Grain Loss	Threshing Efficiency	Se	Output Capacity (kg/s)	Grain Damage by Osueke	Output capacity kg/hr
1.9	0.009569	0.4	0.21	1	0.045	2.2	400	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	10.11059	30.51629	6.873983	0.530786	0.00906508	1.19E-07	0.002038	207.8038	207.8059	1.76522E-10	0.039958	0.039958	0.960042	0.909889	0.006008	0.782123	6.628373
2.4	0.012295	0.4	0.21	1	0.045	2.2	500	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	12.29557	36.31922	8.592479	0.424628		4.91E-07	0.004091	238.875	238.8791	8.45656E-07	0.043603	0.043604	0.956397	0.905748	0.007684	0.787352	12.66242
2.8	0.0131	0.4	0.21	1	0.045	2.2	600	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	16.61716	43.81109	10.31098	0.353857		1.03E-06	0.006277	274.5943	274.6006	1.78006E-05	0.029362	0.02938	0.970638	0.917669	0.008295	0.763945	14.8623
3.3	0.016393	0.4	0.21	1	0.045	2.2	700	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	18.07449	49.45887	12.02947	0.303306		3.19E-06	0.010692	314.9617	314.9724	0.000558099	0.037281	0.03784	0.962719	0.910216	0.010296	0.777996	22.06517
3.8	0.020202	0.4	0.21	1	0.045	2.2	800	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	19.1569	54.90433	13.74797	0.265393		8.92E-06	0.017209	359.9772	359.9944	0.004898143	0.047337	0.052235	0.952663	0.901208	0.012562	0.792305	30.22427
4.2	0.021352	0.4	0.21	1	0.045	2.2	900	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	22.9393	62.29209	15.46646	0.235905		1.5E-05	0.023021	409.6408	409.6638	0.01141065	0.038895	0.050306	0.961105	0.908343	0.013383	0.780515	33.17773
4.7	0.026906	0.4	0.21	1	0.045	2.2	1000	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	22.47469	66.72416	17.18496	0.212314		4.12E-05	0.035813	463.9525	463.9883	0.040969751	0.057096	0.098066	0.942904	0.892529	0.01657	0.803721	44.65138
5.2	0.023622	0.4	0.21	1	0.045	2.2	1100	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	30.97475	77.35335	18.90345	0.193013		3.71E-05	0.038045	522.9122	522.9503	0.036580688	0.027678	0.064259	0.972322	0.91823	0.014966	0.76051	38.87912
5.7	0.032258	0.4	0.21	1	0.045	2.2	1200	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	26.99381	79.54271	20.62195	0.176929		0.000123	0.061829	586.5201	586.5821	0.108534717	0.05695	0.165485	0.94305	0.892444	0.019864	0.803563	56.51066
6.1	0.032258	0.4	0.21	1	0.045	2.2	1300	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	31.68024	87.70983	22.34045	0.163319		0.000156	0.072563	654.7761	654.8488	0.12875251	0.044852	0.173605	0.955148	0.902746	0.020093	0.789051	57.33616
6.6	0.032258	0.4	0.21	1	0.045	2.2	1400	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	36.74158	96.04585	24.05894	0.151653		0.000195	0.084156	727.6802	727.7645	0.149054325	0.035324	0.184379	0.964676	0.911083	0.020279	0.774801	58.00418
7.1	0.032258	0.4	0.21	1	0.045	2.2	1500	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	42.17783	104.5405	25.77744	0.141543		0.000239	0.096608	805.2323	805.3292	0.169221267	0.027821	0.197042	0.972179	0.917888	0.02043	0.760808	58.54945
7.5	0.032258	0.4	0.21	1	0.045	2.2	1600	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	47.989	113.185	27.49593	0.132696		0.000291	0.109919	887.4326	887.5428	0.18909346	0.021911	0.211004	0.978089	0.923491	0.020555	0.747068	58.9984
8.0	0.032258	0.4	0.21	1	0.045	2.2	1700	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	54.17508	121.9715	29.21443	0.124891		0.000348	0.124088	974.281	974.4054	0.208557086	0.017256	0.225813	0.982744	0.928144	0.020659	0.733576	59.37132
8.5	0.032258	0.4	0.21	1	0.045	2.2	1800	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	60.73608	130.8931	30.93293	0.117952		0.000414	0.139116	1065.777	1065.917	0.22753373	0.013591	0.241124	0.986409	0.932044	0.020745	0.720327	59.68377
8.9	0.032258	0.4	0.21	1	0.045	2.2	1900	48.83	0.21	0.04	0.06	0.0018	0.0085	0.016	0.02	67.67199	139.9439	32.65142	0.111744		0.000487	0.155002	1161.922	1162.077	0.245971892	0.010704	0.256675	0.989296	0.935339	0.020819	0.707318	59.94783

Plate A1: Design simulation inputs variables and performance outputs.



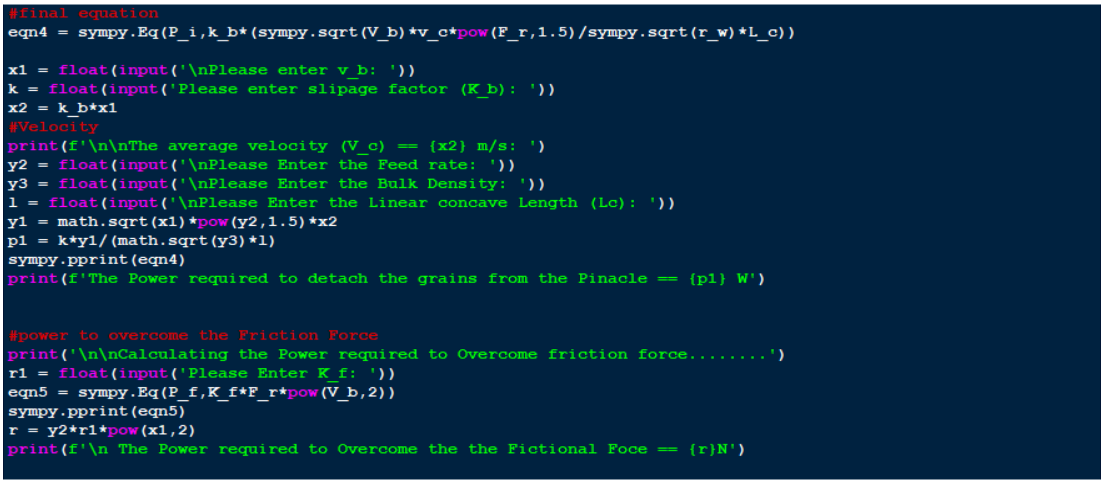
```
#PYTHON V3
from os import system
from datetime import datetime

#hello msg
print('HELLO' + str('PATRICK \n') + str('WELCOME TO PYTHON'))
```



```
'''
================================================================================

MODELLING AND OPTIMIZATION OF DESIGN PARAMETERS AND\
PERFORMANCE OF A STATIONARY SOLAR THRESHER FOR COMMON BEAN
             (PHASEOLUS VULGARIS L)

             PYTHON 3.8 v1
================================================================================
'''

#libraries and modules
import datetime
import os
import math
import sympy
import pandas
import scipy
import numpy

#globals
k_b = 0.4
```

Plate A2: Python software opening window.

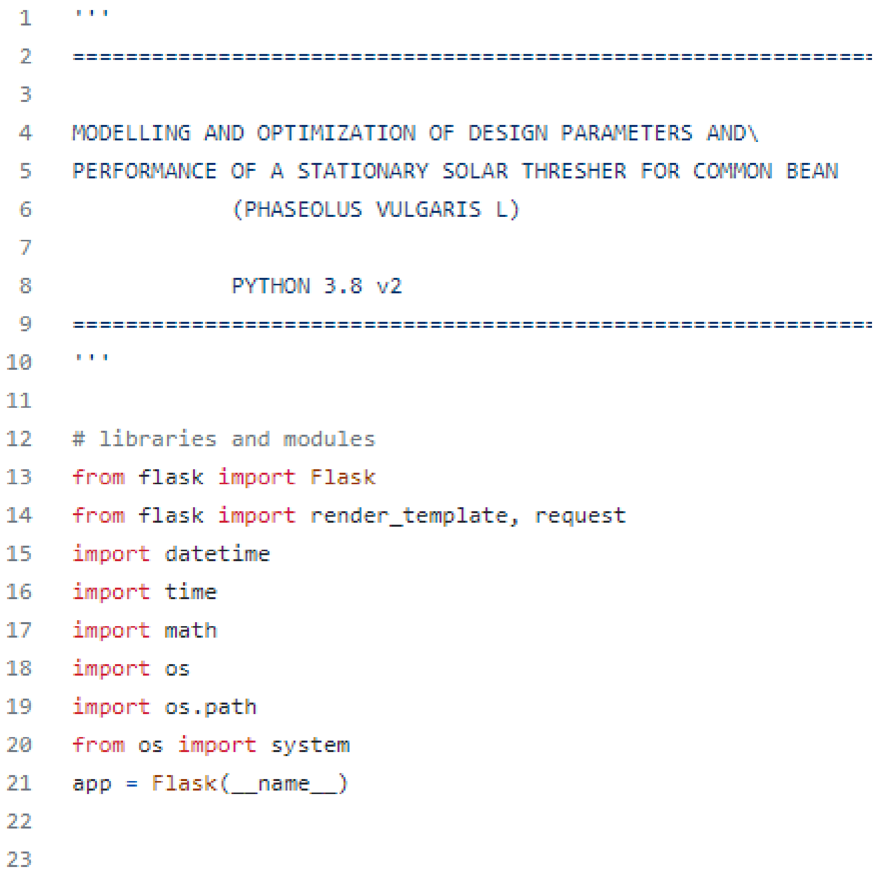
Plate A3: Inbuilt libraries like math, date, time and system for python.



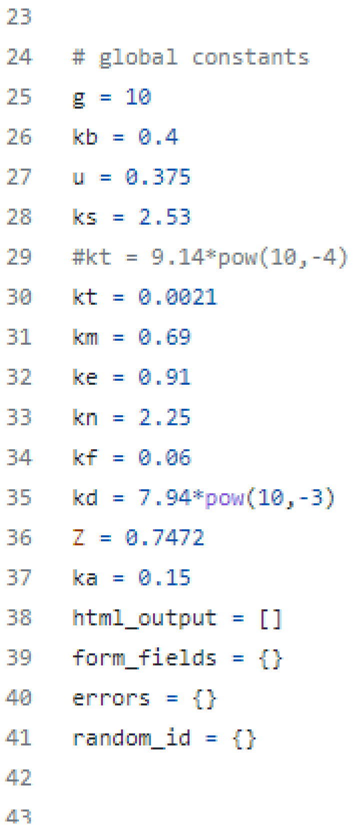
```
#final equation
eqn4 = sympy.Eq(P_i,k_b*(sympy.sqrt(V_b)*v_c*pow(F_r,1.5)/sympy.sqrt(r_w)*L_c))

x1 = float(input('\nPlease enter v_b: '))
k = float(input('Please enter slipage factor (K_b): '))
x2 = k_b*x1
#Velocity
print(f'\n\nThe average velocity (V_c) == {x2} m/s: ')
y2 = float(input('\nPlease Enter the Feed rate: '))
y3 = float(input('\nPlease Enter the Bulk Density: '))
l = float(input('\nPlease Enter the Linear concave Length (Lc): '))
y1 = math.sqrt(x1)*pow(y2,1.5)*x2
p1 = k*y1/(math.sqrt(y3)*l)
sympy.pprint(eqn4)
print(f'The Power required to detach the grains from the Pinacle == {p1} W')


#power to overcome the Friction Force
print('\n\nCalculating the Power required to Overcome friction force........')
r1 = float(input('Please Enter K_f: '))
eqn5 = sympy.Eq(P_f,K_f*F_r*pow(V_b,2))
sympy.pprint(eqn5)
r = y2*r1*pow(x1,2)
print(f'\n The Power required to Overcome the the Fictional Foce == {r}N')
```

Plate A4: Python software programming user interface.

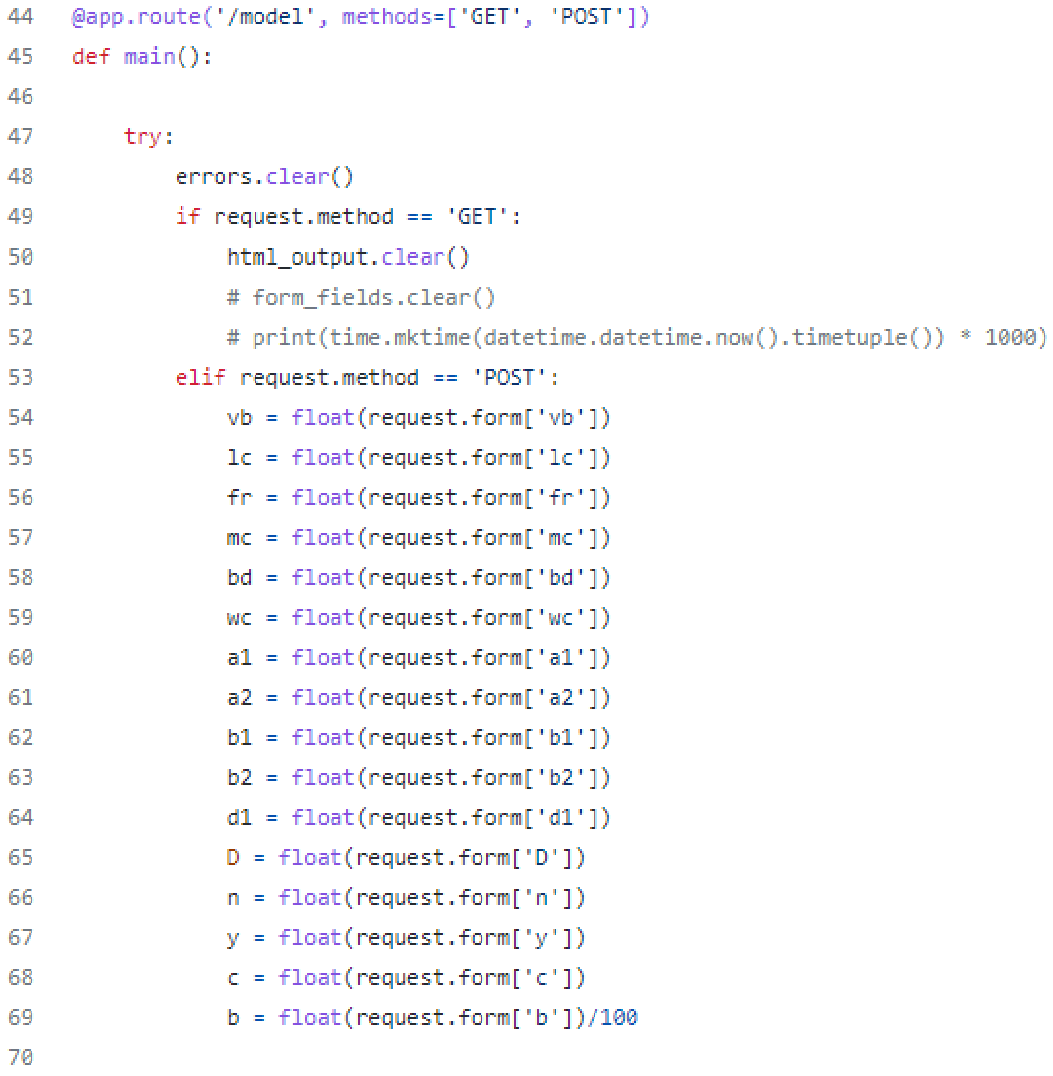
Appendix II: Programming code used for simulation



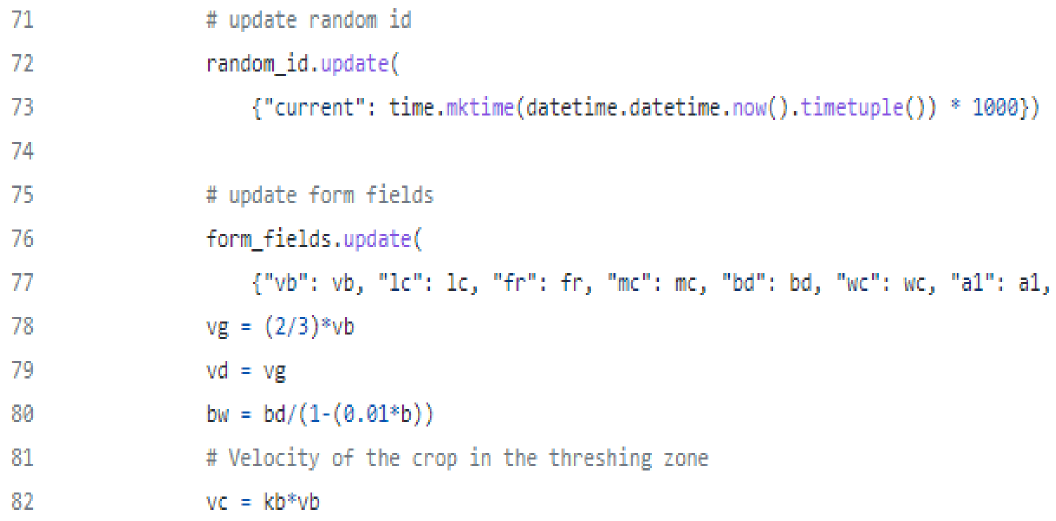
```
'''
============================================================

MODELLING AND OPTIMIZATION OF DESIGN PARAMETERS AND\
PERFORMANCE OF A STATIONARY SOLAR THRESHER FOR COMMON BEAN
            (PHASEOLUS VULGARIS L)

            PYTHON 3.8 v2
============================================================
'''

# libraries and modules
from flask import Flask
from flask import render_template, request
import datetime
import time
import math
import os
import os.path
from os import system
app = Flask(__name__)


```



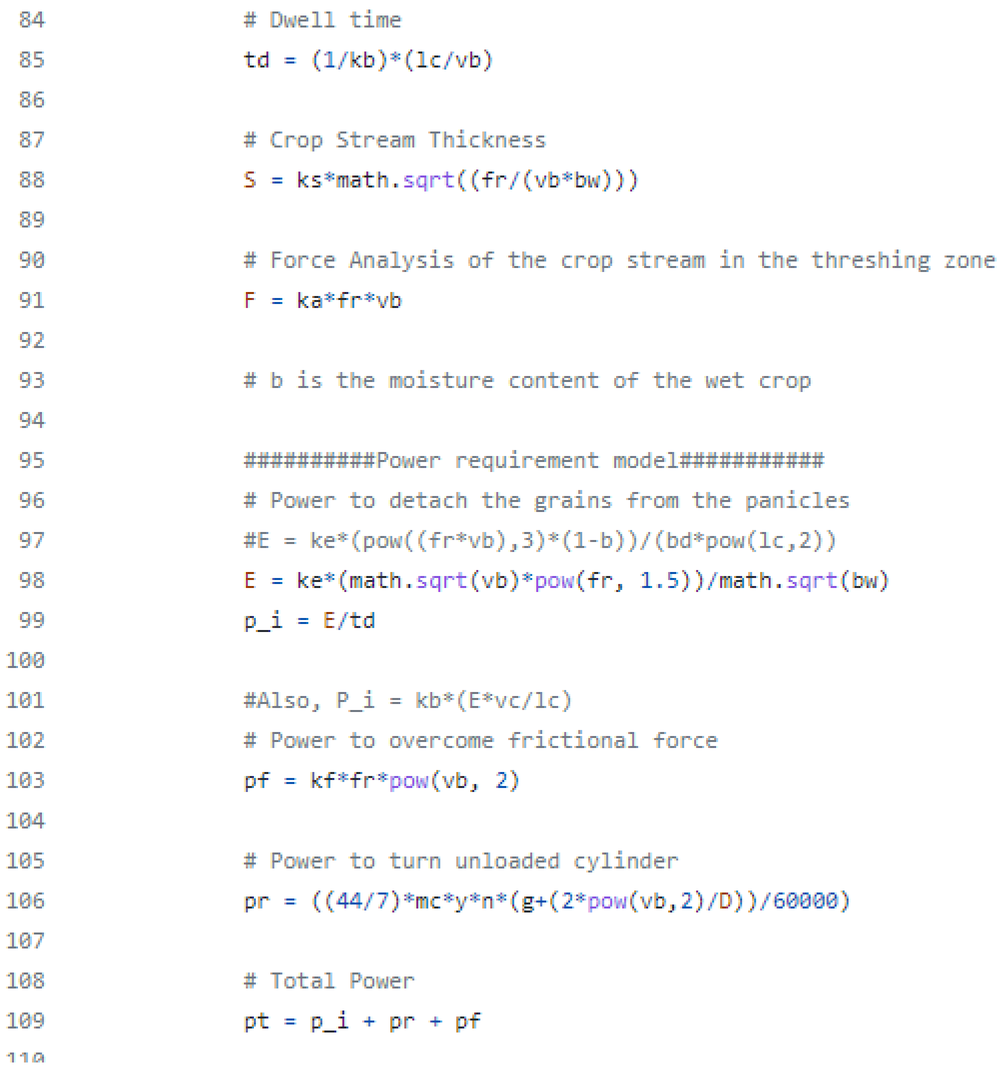
```

# global constants
g = 10
kb = 0.4
u = 0.375
ks = 2.53
#kt = 9.14*pow(10,-4)
kt = 0.0021
km = 0.69
ke = 0.91
kn = 2.25
kf = 0.06
kd = 7.94*pow(10,-3)
Z = 0.7472
ka = 0.15
html_output = []
form_fields = {}
errors = {}
random_id = {}


```



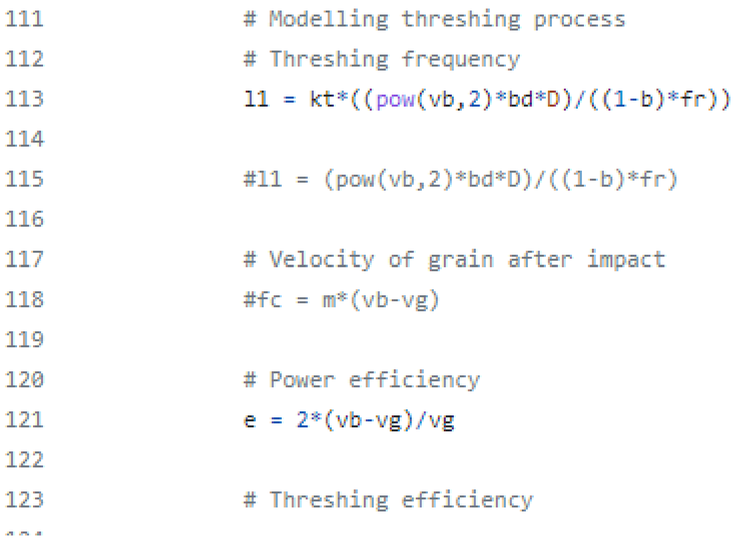
```
@app.route('/model', methods=['GET', 'POST'])
def main():

    try:
        errors.clear()
        if request.method == 'GET':
            html_output.clear()
            # form_fields.clear()
            # print(time.mktime(datetime.datetime.now().timetuple()) * 1000)
        elif request.method == 'POST':
            vb = float(request.form['vb'])
            lc = float(request.form['lc'])
            fr = float(request.form['fr'])
            mc = float(request.form['mc'])
            bd = float(request.form['bd'])
            wc = float(request.form['wc'])
            a1 = float(request.form['a1'])
            a2 = float(request.form['a2'])
            b1 = float(request.form['b1'])
            b2 = float(request.form['b2'])
            d1 = float(request.form['d1'])
            D = float(request.form['D'])
            n = float(request.form['n'])
            y = float(request.form['y'])
            c = float(request.form['c'])
            b = float(request.form['b'])/100

```



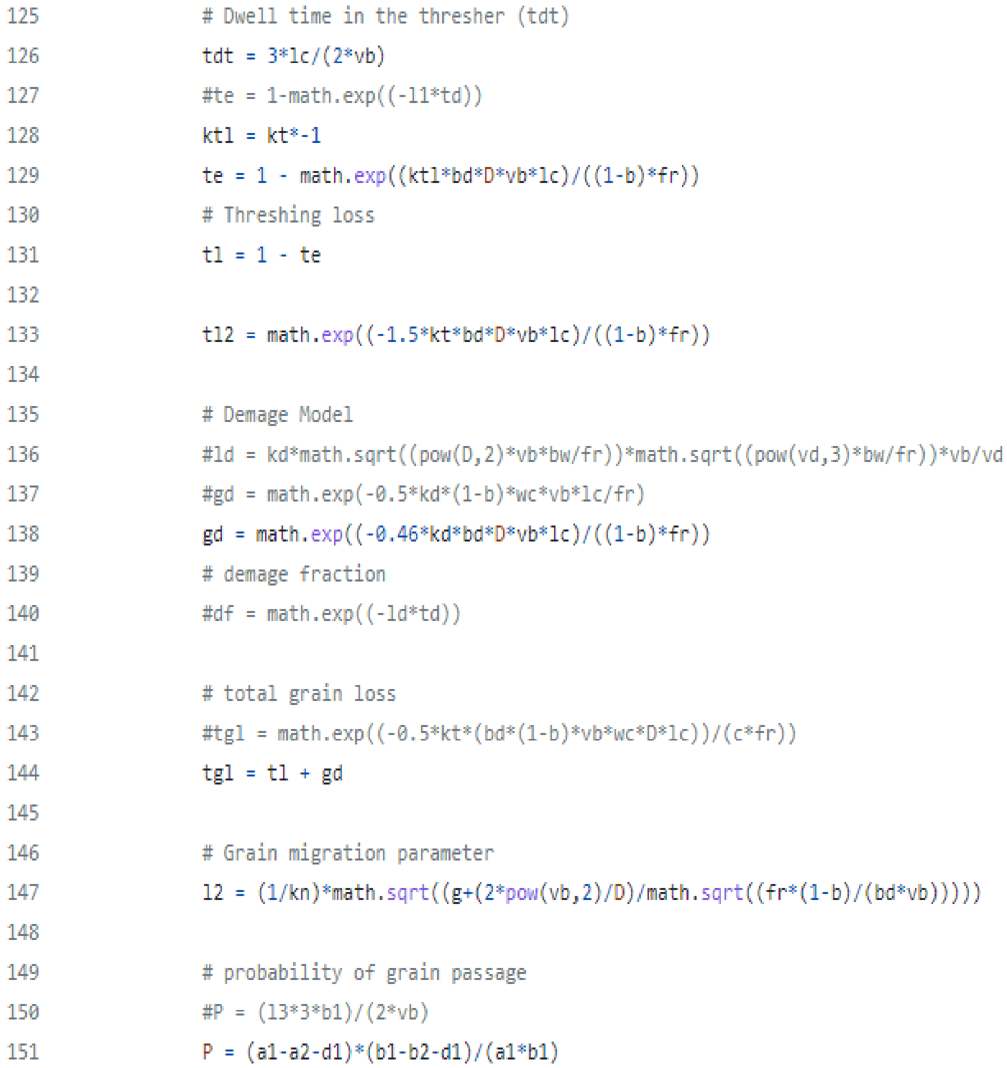
```
        # update random id
        random_id.update(
            {"current": time.mktime(datetime.datetime.now().timetuple()) * 1000})

        # update form fields
        form_fields.update(
            {"vb": vb, "lc": lc, "fr": fr, "mc": mc, "bd": bd, "wc": wc, "a1": a1,
        vg = (2/3)*vb
        vd = vg
        bw = bd/(1-(0.01*b))
        # Velocity of the crop in the threshing zone
        vc = kb*vb
```



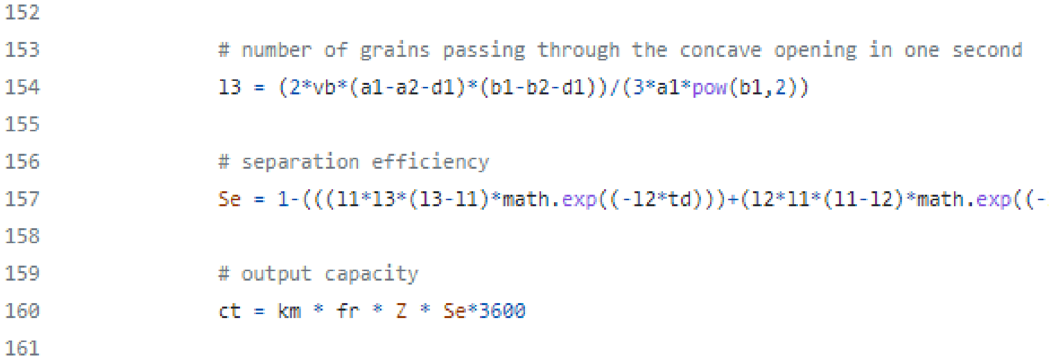
```
# Dwell time
td = (1/kb)*(lc/vb)

# Crop Stream Thickness
S = ks*math.sqrt((fr/(vb*bw)))

# Force Analysis of the crop stream in the threshing zone
F = ka*fr*vb

# b is the moisture content of the wet crop

##########Power requirement model###########
# Power to detach the grains from the panicles
#E = ke*(pow((fr*vb),3)*(1-b))/(bd*pow(lc,2))
E = ke*(math.sqrt(vb)*pow(fr, 1.5))/math.sqrt(bw)
p_i = E/td

#Also, P_i = kb*(E*vc/lc)
# Power to overcome frictional force
pf = kf*fr*pow(vb, 2)

# Power to turn unloaded cylinder
pr = ((44/7)*mc*y*n*(g+(2*pow(vb,2)/D))/60000)

# Total Power
pt = p_i + pr + pf
```



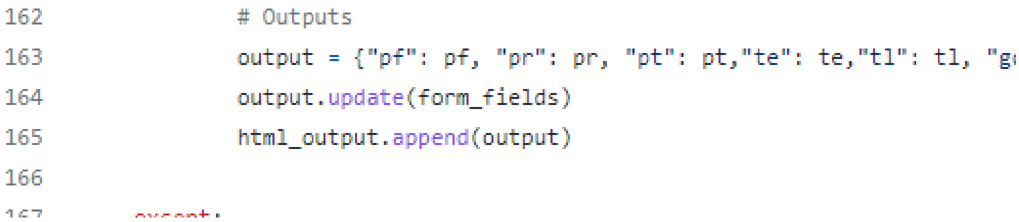
```
# Modelling threshing process
# Threshing frequency
l1 = kt*((pow(vb,2)*bd*D)/((1-b)*fr))

#l1 = (pow(vb,2)*bd*D)/((1-b)*fr)

# Velocity of grain after impact
#fc = m*(vb-vg)

# Power efficiency
e = 2*(vb-vg)/vg

# Threshing efficiency
```



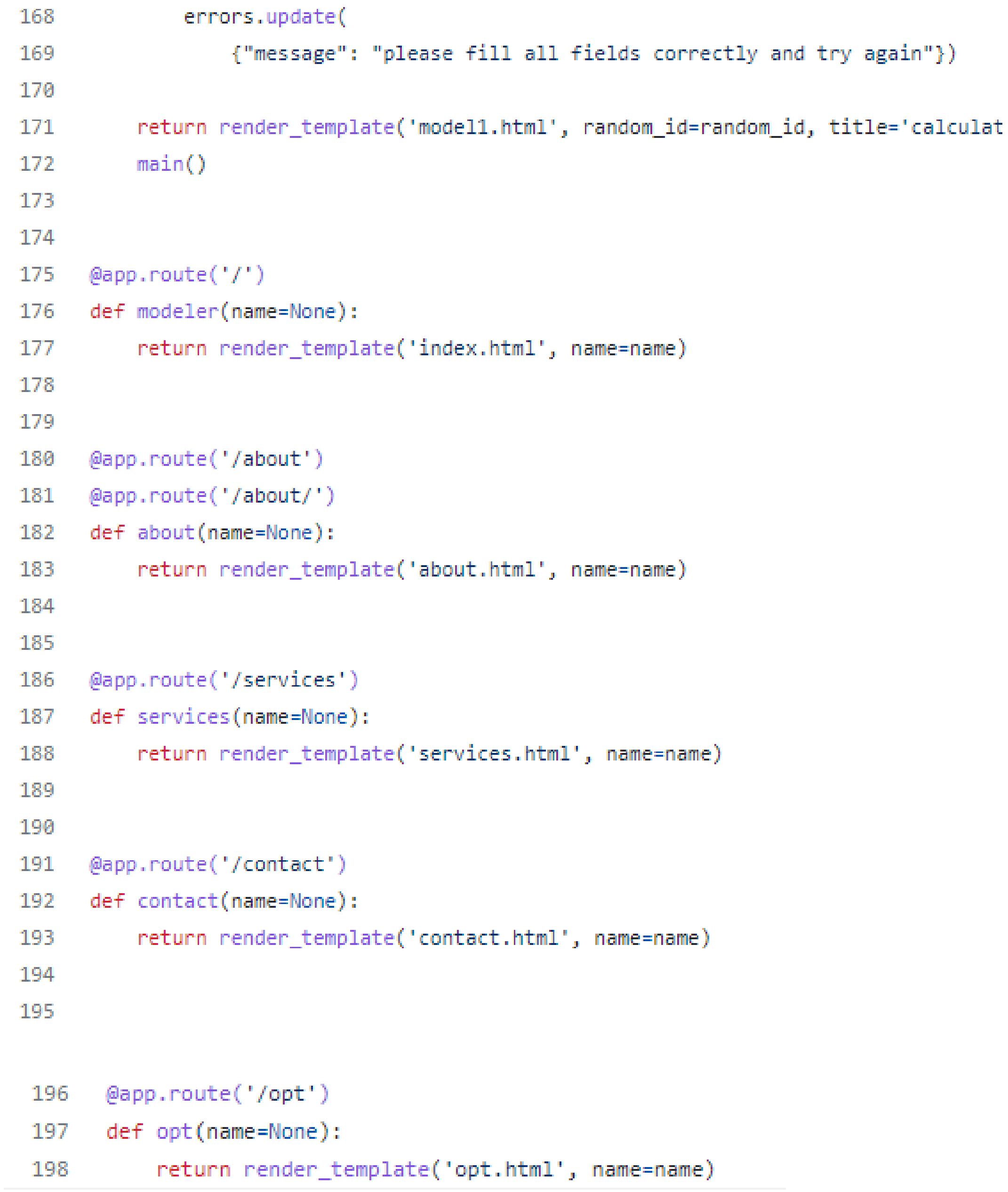
```
            # Dwell time in the thresher (tdt)
            tdt = 3*lc/(2*vb)
            #te = 1-math.exp((-l1*td))
            kt1 = kt*-1
            te = 1 - math.exp((kt1*bd*D*vb*lc)/((1-b)*fr))
            # Threshing loss
            tl = 1 - te

            tl2 = math.exp((-1.5*kt*bd*D*vb*lc)/((1-b)*fr))

            # Demage Model
            #ld = kd*math.sqrt((pow(D,2)*vb*bw/fr))*math.sqrt((pow(vd,3)*bw/fr))*vb/vd
            #gd = math.exp(-0.5*kd*(1-b)*wc*vb*lc/fr)
            gd = math.exp((-0.46*kd*bd*D*vb*lc)/((1-b)*fr))
            # demage fraction
            #df = math.exp((-ld*td))

            # total grain loss
            #tgl = math.exp((-0.5*kt*(bd*(1-b)*vb*wc*D*lc))/(c*fr))
            tgl = tl + gd

            # Grain migration parameter
            l2 = (1/kn)*math.sqrt((g+(2*pow(vb,2)/D)/math.sqrt((fr*(1-b)/(bd*vb)))))

            # probability of grain passage
            #P = (l3*3*b1)/(2*vb)
            P = (a1-a2-d1)*(b1-b2-d1)/(a1*b1)
```



```

            # number of grains passing through the concave opening in one second
            l3 = (2*vb*(a1-a2-d1)*(b1-b2-d1))/(3*a1*pow(b1,2))

            # separation efficiency
            Se = 1-(((l1*l3*(l3-l1)*math.exp((-l2*td)))+(l2*l1*(l1-l2)*math.exp((-

            # output capacity
            ct = km * fr * Z * Se*3600

```



```
            # Outputs
            output = {"pf": pf, "pr": pr, "pt": pt,"te": te,"tl": tl, "g
            output.update(form_fields)
            html_output.append(output)

        except:
```



```
        errors.update(
            {"message": "please fill all fields correctly and try again"})

    return render_template('model1.html', random_id=random_id, title='calculat
    main()


@app.route('/')
def modeler(name=None):
    return render_template('index.html', name=name)


@app.route('/about')
@app.route('/about/')
def about(name=None):
    return render_template('about.html', name=name)


@app.route('/services')
def services(name=None):
    return render_template('services.html', name=name)


@app.route('/contact')
def contact(name=None):
    return render_template('contact.html', name=name)


@app.route('/opt')
def opt(name=None):
    return render_template('opt.html', name=name)
```

Plate A5: Program code used for simulation

Appendix III: Sample Data collection table

Table B1: Data collection sheet

Cylinder speed	Wt of unthreshed sample g+ straw	Wt of threshed grains	Wt of damaged grains	Wt of unthreshed grains	Wt of unthreshed grains+ damaged grains	Wt of threshed grain at Lc1	Wt of threshed grain at Lc2	Wt of threshed grain at Lc3	Wt of threshed grain at Lc4	Wt of threshed grain at exit	Time of test run	Power consumed per throughput
400												
500												
600												
700												
800												
900												
1000												
1100												
1200												

Appendix IV: S/N for performance indicators of bean thresher

Table B2: Signal to noise ratio of simulation model results

Exp	v	ρ	Q	w	β	M_c	P_T	S/N (P_T)	G_d	S/N (G_d)	T_e	S/N (T_e)	C_T	S/N (C_T)
1	1.9	44	0.01	0.2	15	2	207.3	-46.3	3.4	-10.55	42.	32.5	22	26.8
2	1.9	46	0.02	0.4	17.5	4	284.6	-49.1	2.6	-8.28	45	32.9	37	31.5
3	1.9	48	0.03	0.6	20	6	361.9	-51.2	1.9	-5.86	47	33.4	48	33.6
4	1.9	50	0.04	0.8	22.5	8	439.2	-52.9	1.5	-3.29	50	33.9	57	35.1
5	1.9	52	0.05	1	25	10	516.5	-54.3	1.1	-0.55	52	34.3	65	36.2
6	2.8	44	0.02	0.6	22.5	10	1284	-62.2	6.2	-15.77	84	38.4	45	33.0
7	2.8	46	0.03	0.8	25	2	360.8	-51.1	6.9	-16.74	82	38.3	63	35.9
8	2.8	48	0.04	1	15	4	591.6	-55.4	9.9	-19.92	78	37.8	75	37.5
9	2.8	50	0.05	0.2	17.5	6	822.4	-58.3	67	-36.55	23	27.1	88	38.8
10	2.8	52	0.1	0.4	20	8	1053	-60.4	1.4	-3.02	94	39.4	24	27.5
11	3.8	44	0.03	1	17.5	8	1972	-65.9	14	-23.14	94	39.5	66	36.4
12	3.8	46	0.04	0.2	20	10	2432	-67.7	73	-37.27	37	31.3	85	38.6
13	3.8	48	0.05	0.4	22.5	2	590.6	-55.4	58	-35.30	55	34.7	102	40.2
14	3.8	50	0.01	0.6	25	4	1051	-60.4	1.3	-2.07	99	39.9	24	27.6
15	3.8	52	0.02	0.8	15	6	1511	-63.6	6.9	-16.80	98	39.8	47	33.4
16	4.7	44	0.04	0.4	25	6	2429	-67.7	62	-35.83	71	37.1	90	39.1
17	4.7	46	0.05	0.6	15	8	3196	-70.1	59	-35.38	74	37.5	106	40.5
18	4.7	48	0.01	0.8	17.5	10	3962	-72.0	2.2	-6.90	99	40.0	24	27.6
19	4.7	50	0.02	1	20	2	896.4	-59.1	7.7	-17.77	99	39.9	47	33.5
20	4.7	52	0.03	0.2	22.5	4	1663	-64.4	69	-36.82	61	35.7	70	36.9
21	5.7	44	0.05	0.8	20	4	2427	-67.7	56	-34.99	90	39.1	112	40.9
22	5.7	46	0.01	1	22.5	6	3575	-71.1	2.1	-6.23	100	40.0	24	27.6
23	5.7	48	0.02	0.2	25	8	4724	-73.5	66	-36.36	82	38.2	48	33.5
24	5.7	50	0.03	0.4	15	10	5872	-75.4	60	-35.54	88	38.8	70	36.9
25	5.7	52	0.04	0.6	17.5	2	1279	-62.1	54	-34.62	92	39.2	92	39.3

Appendix V: Calculation of coefficient of correlation and determination

Table B3: Calculation of coefficient of correlation and determination for simulated power required

	Peripheral pegs velocity (X)	**Simulated power required (Y)**	**XY**	**X^2**	**Y^2**
	1.9	207.8	391.51	3.55	43183.27
	2.4	238.9	562.56	5.55	57063.23
	2.8	274.6	776.02	7.99	75405.48
	3.3	315.0	1038.46	10.87	99207.61
	3.8	360.0	1356.46	14.20	129595.97
	4.2	409.7	1736.56	17.97	167824.44
	4.7	464.0	2185.38	22.18	215285.15
	5.2	523.0	2709.41	26.84	273477.04
	5.7	586.6	3315.36	31.95	344078.52
SUM	**33.9**	**3379.4**	**14071.7**	**141.1**	**1405120.7**

Coefficient of correlation (R) **0.993**

$$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$$

Coefficient of determination (R^2) **0.987**

Table B4: Calculation of coefficient of correlation and determination for actual power required

Peripheral pegs velocity	**Actual power required**	**XY**	**X^2**	**Y^2**
1.884	276	519.98	3.549456	76176
2.355	288	678.24	5.546025	82944
2.826	302	853.45	7.986276	91204
3.297	326	1074.82	10.87021	106276
3.768	371	1397.93	14.19782	137641
4.239	407	1725.27	17.96912	165649
4.71	453	2133.63	22.1841	205209
5.181	496	2569.78	26.84276	246016
5.652	537	3035.12	31.9451	288369
33.912	**3456**	**13988.23**	**141.09**	**1399484**

Correlation coefficient (R) $r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$	**0.984**
Coefficient of determination (R^2)	0.968

Table B5: Calculation of coefficient of correlation and determination for simulated grain damage

Peripheral pegs velocity (X)	Simulated grain damage (Y)	XY	X^2	Y^2
1.884	0.0	3.32568E-08	3.549456	0.0
2.355	0.0	0.000199152	5.546025	0.0
2.826	0.0	0.005030454	7.986276	0.0
3.297	0.1	0.18400511	10.870209	0.0
3.768	0.5	1.845620171	14.197824	0.2
4.239	1.1	4.836974559	17.969121	1.3
4.71	4.1	19.29675279	22.1841	16.8
5.181	3.7	18.95245467	26.842761	13.4
5.652	10.9	61.34382223	31.945104	117.8
33.912	**20.29706947**	**106.4648592**	**141.090876**	**149.5095867**
Coefficient of correlation (R) $r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$				**0.80696**
Coefficient of determination (R^2)				**0.651**

Table B6: Calculation of coefficient of correlation and determination for actual power grain damage

Peripheral pegs velocity	Actual grain damage	XY	X^2	Y^2
1.884	0	0	3.549456	0
2.355	0.021308332	0.050181121	5.546025	0.000454045
2.826	0.772681954	2.183599202	7.986276	0.597037402
3.297	0.638569604	2.105363985	10.870209	0.407771139
3.768	1.638672675	6.17451864	14.197824	2.685248136
4.239	5.833875515	24.72979831	17.969121	34.03410353
4.71	6.998679494	32.96378042	22.1841	48.98151467
5.181	12.69296741	65.76226415	26.842761	161.1114217
5.652	13.83383383	78.18882883	31.945104	191.3749585
33.912	**42.43058882**	**212.1583347**	**141.090876**	**439.1925091**

Coefficient of correlation (R) $r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$	**0.926616**
Coefficient of determination (R^2)	**0.859**

Table B7: Calculation of coefficient of correlation and determination for simulated threshing efficiency

Peripheral velocity pegs (X)	**Simulated threshing Efficiency (Y)**	**XY**	**X^2**	**Y^2**
1.884	94.3	177.6612	3.549	8892.49
2.355	95.1	223.9605	5.546	9044.01
2.826	95.7	270.4482	7.986	9158.49
3.297	96	316.512	10.870	9216
3.768	96.1	362.1048	14.198	9235.21
4.239	96.2	407.7918	17.969	9254.44
4.71	96.3	453.573	22.184	9273.69
5.181	97.1	503.0751	26.843	9428.41
5.652	97.2	549.3744	31.945	9447.84
33.912	**864**	**3264.501**	**141.091**	**82950.58**
Coefficient of correlation (R) $r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$				**0.956236**
Coefficient of determination (R^2)				**0.914387**

Table B8: Calculation of coefficient of correlation and determination for actual threshing efficiency

Peripheral pegs velocity (X)	**Actual threshing efficiency**	**XY**	**X^2**	**Y^2**
1.9	98.1	184.75	3.55	9616.53
2.4	99.1	233.44	5.55	9826.03
2.8	100.0	282.46	7.99	9990.03
3.3	100	329.7	10.87	10000.00
3.8	100	376.8	14.20	10000.00
4.2	100	423.9	17.97	10000.00
4.7	100	471	22.18	10000.00
5.2	100	518.1	26.84	10000.00
5.7	100	565.2	31.95	10000.00
33.9	**897.1**	**3385.4**	**141.1**	**89432.6**
Coefficient of correlation (R)				**0.711499**

$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$	
Coefficient of determination (R^2)	**0.5062**

Table B9: Calculation of coefficient of correlation and determination for simulated throughput capacity

Linear Velocity	**Simulated output capacity**	**XY**	**X^2**	**Y^2**
1.9	6.6	12.5	3.5	43.9
2.4	12.7	29.8	5.5	160.3
2.8	14.9	42.0	8.0	220.9
3.3	22.1	72.7	10.9	486.9
3.8	30.2	113.9	14.2	913.5
4.2	33.2	140.6	18.0	1100.8
4.7	44.7	210.3	22.2	1993.7
5.2	38.9	201.4	26.8	1511.6
5.7	56.5	319.4	31.9	3193.5
33.9	**259.7**	**1142.7**	**141.1**	**9625.1**
Coefficient of correlation (R) $r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$				**0.951**
Coefficient of determination (R^2)				**0.97508**

Table B10: Calculation of coefficient of correlation and determination for actual throughput capacity

Linear Velocity	**Actual output capacity**	**XY**	**X^2**	**Y^2**
1.9	12.3	23.2	3.5	151.5
2.4	17.3	40.8	5.5	299.6
2.8	15.8	44.6	8.0	248.6
3.3	23.1	76.2	10.9	533.8
3.8	29.6	111.5	14.2	875.4
4.2	29.5	125.2	18.0	872.4
4.7	42.8	201.5	22.2	1830.8
5.2	37.2	192.6	26.8	1382.6
5.7	48.3	273.2	31.9	2336.6
33.9	**255.9**	**1088.8**	**141.1**	**8531.5**

Coefficient of correlation (R) $r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$	**0.9279**
Coefficient of determination (R^2)	**0.9633**

Appendix VI: Calculation of paired two sample t-test means

Table B11: Paired two sample t-test for means of simulated and actual power required

	Simulated variable	*Actual Variable*
Mean	375.493	384
Variance	17020.74	9047.5
Observations	9	9
Pearson Correlation	0.996355	
Hypothesized Mean Difference	0	
df	8	
t Stat	-0.69725	
P(T<=t) one-tail	0.252701	
t Critical one-tail	1.859548	
P(T<=t) two-tail	0.505402	
t Critical two-tail	2.306004	

Table B12: Paired two sample t-test for means of simulated and actual grain damage

	Simulated Variable 1	*Actual Variable 2*
Mean	2.255229941	4.736954313
Variance	12.96687848	29.69241444
Observations	9	9
Pearson Correlation	0.870276546	
Hypothesized Mean Difference	0	
df	8	
t Stat	-2.552715489	
P(T<=t) one-tail	0.017015272	
t Critical one-tail	1.859548038	
P(T<=t) two-tail	0.034030544	
t Critical two-tail	2.306004135	

Table B13: Paired two sample ttest for means of simulated and actual threshing efficiency

	Simulated Variable 1	*Actual Variable 2*
Mean	99.68226912	96.11111111
Variance	0.450698362	0.913611111
Observations	9	9
Pearson Correlation	0.859123091	
Hypothesized Mean Difference	0	
df	8	
t Stat	20.94121144	
P(T<=t) one-tail	1.41875E-08	
t Critical one-tail	1.859548038	
P(T<=t) two-tail	2.83749E-08	
t Critical two-tail	2.306004135	

Table B14: Paired two sample t-test for means of simulated and actual throughput capacity

	Simulated Variable 1	*Actual Variable 2*
Mean	28.85127	28.43612
Variance	266.6906	156.749
Observations	9	9
Pearson Correlation	0.992414	
df	8	
t Stat	0.296673	
P(T<=t) one-tail	0.387136	
t Critical one-tail	1.859548	
P(T<=t) two-tail	0.774273	
t Critical two-tail	2.306004	

Appendix VII: Analysis of variance for performance indicators

Table B15: ANOVA for grain damage

Source of variation	Degrees of freedom (DOF)	Sum of square (SS)	Mean Sum of Squares	F-Ratio	F-Tabulated	Factor % Contribution
Total	24	4623.2				
Peripheral velocity	4	1735.9	434.0	8.3	2.9	37.5
Bulk density of beans	4	98.9	24.7	0.5	2.9	2.1
Feedrate	4	1715.9	429.0	8.2	2.9	37.1
Concave width	4	1025.9	256.5	4.9	2.9	22.2
Moisture content	4	342.5	85.6	1.6	2.9	7.4
Mass of cylinder	4	342.5	85.6	1.6	2.9	7.4
Error	19	991.6	52.2			

Table B16: ANOVA for threshing efficiency

Source of variation	Degrees of freedom (DOF)	Sum of squares (SS)	Mean Sum of Squares	F-Ratio	F-Tabulated	Factor % Contribution
Total	24	277.0				
Peripheral velocity	4	93.0	23.2	8.0	2.9	33.6
Bulk density of beans	4	12.1	3.0	1.0	2.9	4.4
Feedrate	4	49.0	12.3	4.2	2.9	17.7
Concave width	4	99.4	24.8	8.5	2.9	35.9
Moisture content	4	10.0	2.5	0.9	2.9	3.6
Mass of cylinder	4	13.7	3.4	1.2	2.9	4.9
Error	19	55.4	2.9			

Table B17: ANOVA for throughput capacity

Source of variation	Degrees of freedom (DOF)	Sum of squares (SS)	Mean Sum of Squares	F-Ratio	F-Tabulated	Factor % Contribution
Total	24	485.0				
Peripheral velocity	4	30.3	7.6	1.5	2.9	6.2
Bulk density of beans	4	2.4	0.6	0.1	2.9	0.5
Feedrate	4	448.2	112.1	21.9	2.9	92.4
Concave width	4	2.0	0.5	0.1	2.9	0.4
Moisture content	4	1.0	0.2	0.0	2.9	0.2
Mass of cylinder	4	1.8	0.4	0.1	2.9	0.4

Error	19	97.1	5.1	1.0

Table B18: ANOVA for power required for threshing

Source of variation	Degrees of freedom (DOF)	Sum of squares (SS)	Mean Sum of Squares	F-Ratio	F-Tabulated	Factor % Contribution
Total	24	1577.0				
Peripheral velocity	4	1154.2	288.5	17.37	2.9	73.19
Bulk density of beans	4	3.4	0.9	0.05	2.9	0.22
Feedrate	4	4.0	1.0	0.06	2.9	0.26
Concave width	4	3.0	0.7	0.04	2.9	0.19
Moisture content	4	3.2	0.8	0.05	2.9	0.20
Mass of cylinder	4	410.2	102.6	6.17	2.9	26.01
Error	19	315.6	16.6			

Table B 19: Actual and simulated bean damage at different peripheral pegs speed

Peripheral velocity of pegs (m/s)	Simulated bean damage (%)	Actual bean damage (%)
1.88	0.00	0.00
2.36	0.00	0.02
2.83	0.00	0.77
3.30	0.06	0.64
3.77	0.49	1.64
4.24	1.14	5.83
4.71	4.10	7.00
5.18	3.66	12.69
5.65	10.85	13.83

Appendix VIII: Design drawings and sample plates taken during the study

Plate C1: Research team discussing performance of beans thresher.

Plate C2: Side view of the developed common beans thresher.

Plate C3: Common bean thresher prototype used for validation

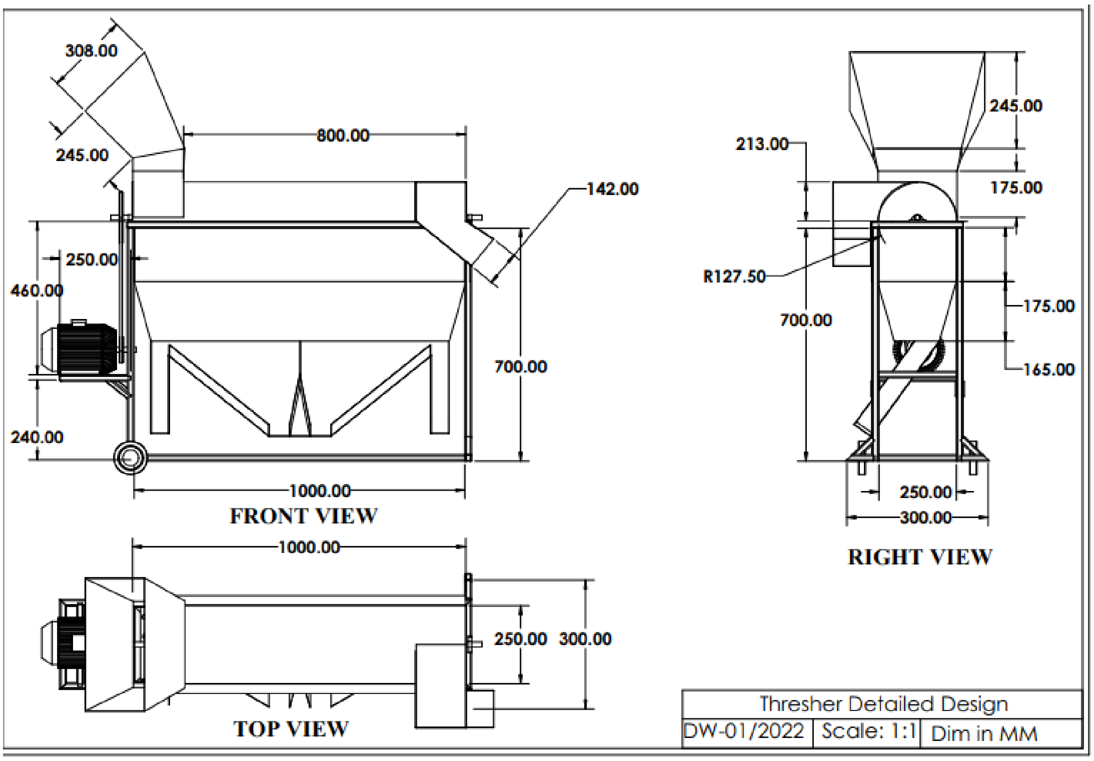
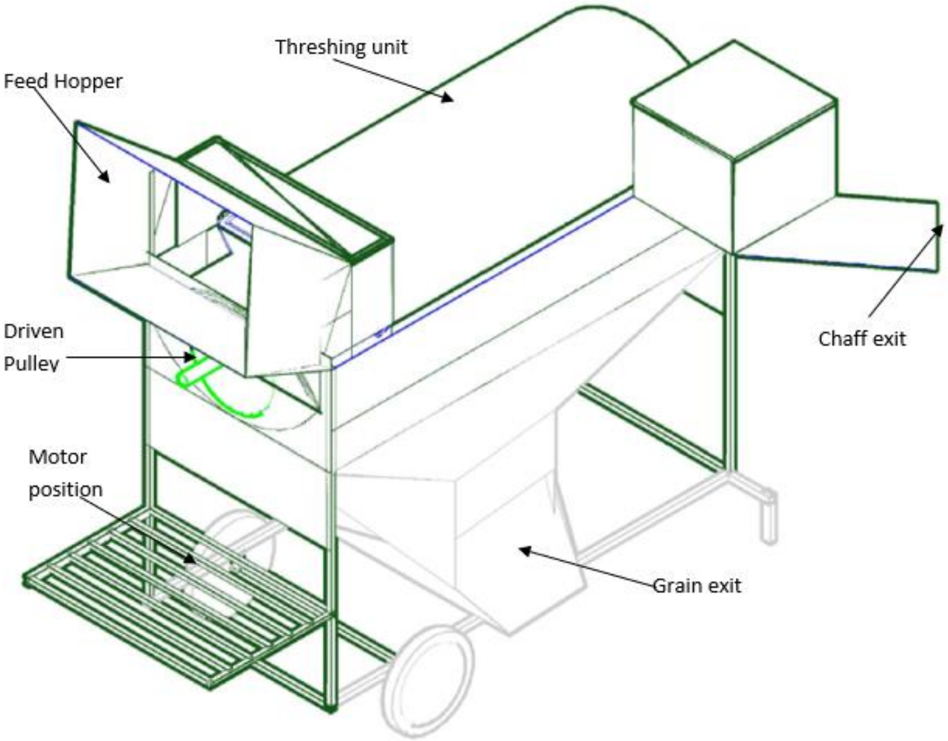


Plate C4: Design drawings for the protype thresher



C5: Front view of common beans thresher

Plate C6: A picture of unthreshed common beans (*Phaseolus Vulgaris L*).

Plate C7: Assorted mechanically damaged grains.