SIMULATION OF DESIGN VARIABLES EFFECT ON PERFORMANCE OF A COMMON BEANS (*Phaseolus vulgaris L*) PORTABLE THRESHER
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KUBASHIRI VIGEZO HUSIKA NA ADHARI ZAKE KWA UTENDAKAZI WA MTAMBO UNAYOJULIKANA WA KUPORA MAHARAGWE

Patrick W. Wamalwa[1)], Christopher L. Kanali[2)], Erick K. Ronoh[2)], Gareth M. Kituu[2)]
[1)] Egerton University, Faculty of Engineering, Agricultural Engineering Department, P.O. Box 536-20115 Egerton/Kenya
[2)] Jomo Kenyatta University of Agriculture and Technology, Department of Agricultural and Biosystems Engineering, P.O. Box 62000 – 00200 Nairobi/Kenya
Correspondent author`s contacts: Tel: +254728920918 E-mail: patrick.wamalwa@egerton.ac.ke
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ABSTRACT
In Kenya, threshing of common beans is mainly made by traditional method using sticks and animal tramping, which are slow, inefficient and tedious. Consequently, there is a need to develop portable threshers locally available on the market for small and medium-scale farmers. The objective of this study was to simulate design variables effect on the performance of a common beans portable thresher. Sizing of design variables and parameters was the key in the development of the bean thresher. This could be achieved by costly experiments or use of prediction mathematical model equation. The later method was used by developing mathematical models from combination of Buckingham Pi theorem and reference to other similar works in literature. The predicting equation for power requirement, grain losses, grain damages, efficiency and throughput capacity were developed and validated using experimental thresher from the same study. The results showed that there was a positive correlation with R^2 of 0.9. Based on actual data and 10% absolute residual error interval, the prediction performance of the developed models was above 77%. The results noted that increase in cylinder peripheral speed of the pegs resulted in the increase in power requirement, bean grains damage, threshing efficiency and throughput capacity. Also increase in effective cylinder diameter caused increase in threshing efficiency and grain damage.

ABSTRACT
Nchini Kenya kupura kwa maharagwe yanayojulikana na wakenya wengi hufaywa kwa njia ya kitamaduni inayohusisha matumizi ya vijiti na wanyama kukanyaga maharagwe. Mbinu hii ina udhahifu kwani ni ya pole, si njia ya kupeana matokeo ya ufanisi na huchosha. Hata hivyo kuna haja ya kubuni mtambo unaobebeka wa kupura maharagwe na upatikane mashinani kwa wakulima wa kiwango kidogo na wastani. Lengo la utafiti huu ilikua ni kubashiri kigezo husika na adhari zake kwa utendakazi wa mtambo unayojulikana wa kupora maharagwe. Idadi ya vigezo mahususi na msingi ya kutumia vigezo hivyo ilikua ni msingi mkuu katika uundaji wa mtambo wa kupora. Hii ilifanywa kwa ujaribati wenye gharama ya juu au kwa kutumia mtindo wa kubashiri wa hesabu unaotokana na nadharia ya Buckingham pi na matumizi ya kazi zingine za kifasihi. Nadharia tete za mahitaji ya umeme, dhana bashiri ya umeme unaohitajika, nafaka ambazo zitaharibika, kiwango cha ufanisi na uwezo wa huru vilibuniwa kwa kutumia mtambo wa kupura wa ujarabati. Matokeo yalionyesha kuwa, kulikuwa na na uhusiano chanya wa nadharia tete na matokeo ya ujarabati yaani uhusiano wa kiwango cha asilimia 90% kwa kuzingatia data halisi na dhana ya mfumo wa ukosefu wa uhalisia ya asilimia 10% na ubashiri wa utendakazi wa miundo maalum ulikuwa Zaidi ya asilimia 77%. Matokeo yalidhihirisha kuwa ongezeko la mzunguko wa kipengo na kasi ya mishalee iliongeza mahitaji ya umeme, uharibifu wa nafaka ya maharagwe, ufanisi wa kuporwa na uwezo wa mtambo. Aidha, ongezo la upana wa kipenyo ulizidisha ufanisi wa kupora na uharibifu wa nafaka.

INTRODUCTION
Common beans (*Phaseolus vulgaris L)* are the second most important staple food crop after maize in most African developing countries Kenya included (*Kiptoo et al*., *2016*). The crop provides a cheap source of protein and 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 it is good for weight reduction.

The production is mainly at the subsistence level by small-scale farmers with limited commercialization, especially during bumper harvest. The crop is grown in almost all regions in Kenya. However, Eastern, Nyanza, Central, Western, and Rift Valley are the major bean-growing regions (*Wortmann, 1998*). Historically, beans are grown for sustenance; however, they have become an important source of income for small-scale Kenyan farmers. As a result of the increase in population, there has been an increasing demand of common beans of over one million metric tonnes against production of 750,000 tonnes in Kenya. The use of traditional human power is one reason for low production coupled with a minor subdivision of land. Therefore, farm mechanization is key towards smart, efficient farming to improve beans production in Kenya (*Groote et al*., *2020*).

In Kenya, post-harvest losses are reported at 20% for cereal grain crops. Drying, threshing, cleaning, packaging, and storage are the primary post-harvest practices (*Mwangi et al*., *2017*). The conventional threshing methods involve beating them with a rod or stick and animal treading, which are tedious, time-consuming, inefficient, and require much energy to the extent of causing blister (*Joshi, 2006*). Grain combine harvesters were popular in overcoming 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, which are not readily available in the market hence the need for design and development (*Duke, 2012; Ndirika, 1997*).

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 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.

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 (α=0.05).

The cylinder/concave threshing mechanism is by far the most commonly used. Its universal adoption appears to be due to 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 (*Ramteke and Sirohi, 2003*). The threshing mechanism adopted for common thresher in this study was the spike or peg tooth type. *Ndirika, (1997),* modelled the performance of stationary spike tooth grain thresher using dimensional analysis and Buckingham Pi theorem. Model development considered moisture content which is very critical on the performance of grain threshers. The formulated models were verified and validated with experimental data from stationary mechanical sorghum and millet thresher. The models were found to correlate and fit well with the experimental data with R^2 values greater than 0.91 at a 0.001 level of significance. Considering the assumptions made, this study has used *Ndirika (1997)* models with little calibration for simulating the performance of common beans thresher.

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 software 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 beans 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.

MATERIALS AND METHODS

1.1 Theoretical models relating to the performance of common beans thresher

The models' development was based on past researchers' mathematical explications to form distinct model expressions for an ideal threshing unit. Dimensional analysis using the concept of Buckingham's Pi theorem and mechanic theory was mainly used. Figure 1 shows the schematic diagram of the modelled threshing unit for the common beans thresher.

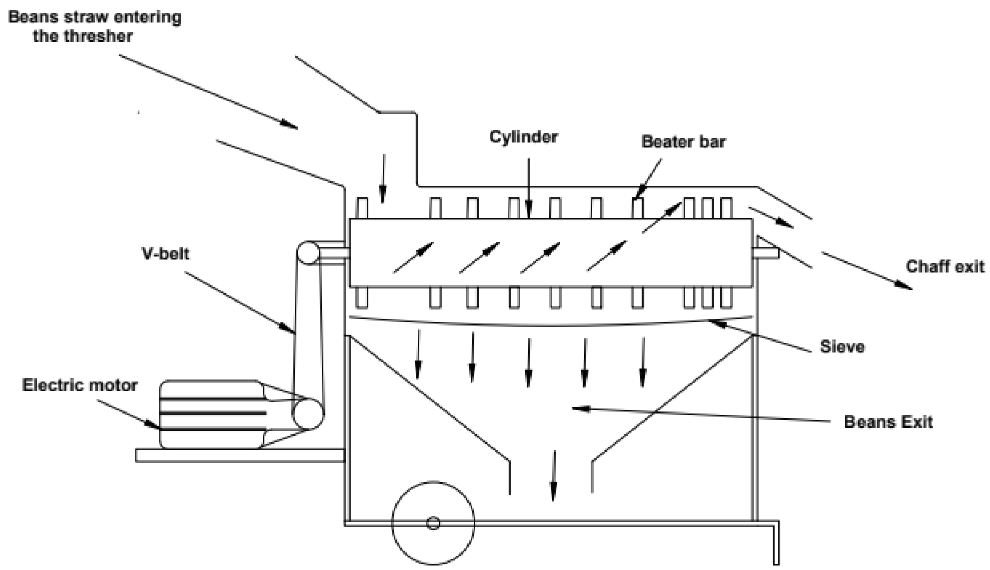

Fig. 1 - Schematic diagram of common beans thresher

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. When the common beans were fed in at the concave entrance, it formed a crop stream which was accelerated by the spike tooth during impact. The common beans were detached from the panicles by a combination of rubbing and impact action. The action involved the application of tensile, compressive, bending, and twisting forces on a head of grain. Threshing was also achieved by the impact occurring when the cylinder pegs strike the bean pods. Separation of the threshed grain from the straws was accomplished through the radial motion of grains relative to the crop streams under the action of gravity and centrifugal force *(Huynh et al., 1982; Ndirika, 1997*). The key models used to describe the threshing unit were; power requirement, threshing efficiency, threshing loss, grain damage, and output capacity.

The power requirement model was a sum of power required to overcome friction, the power required to detach the grains from the pods, and the power required to turn the unloaded cylinder. 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. The power required to detach the grains from the pods was determined by first defining the energy required to detach the grains from the panicles. Let's assume that the variables of importance are the crop velocity, crop bulk density (wet basis), feed rate, concave clearance, concave length, and cylinder diameter. The power required to run the unloaded cylinder was based on the rotational speed without load and the torque required to run the cylinder without load. Therefore Equation 1 was used to predict the total power required for threshing common beans *(Huynh et al., 1982; Osueke 2011 and Ndirika, 1997*).

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

where: 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; g' is the acceleration due to gravity and D is the effective diameter of the cylinder.

The threshing process has been defined by an exponential function (*Huynh et al, 1982; Gregory, 1988*). Therefore, the exponential probability density function was considered for describing and predicting the process performance and various variables influencing threshability.

The process was considered 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. Equation 2 was used to predict the threshing efficiency of common beans thresher.

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

where:

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 is defined in Equation 3, the fraction of unthreshed common beans expressed in percentage.

$$T_L = 1 - T_e \quad (3)$$

Substituting T_e in Equation 2 into Equation 3 resulted into Equation 4, which was used to predict threshing loss.

$$T_L = -e^{\left[\frac{1.4\times K_T\times\rho_d w\times D\times V_p^2 L_c}{(1-\beta)Q_r}\right]} \quad (4)$$

The damage frequency or the mean rate of grain damage was determined using dimensional analysis and applying Buckingham's Pi theorem. The crucial variables influencing damage parameters were assumed to be cylinder velocity, crop bulk density, feed rate, cylinder diameter, and minimum velocity to cause grain damage. Fraction of damaged common beans was further defined based on integral exponential probability density function within dwell time in the threshing zone (*Huynh et al., 1982; Gregory, 1988*).

Equation 5 was used to express the fraction of the damaged common beans after impact by the pegs. Db is the fraction of damaged common beans grains in the equation, and K_d is the damaged constant.

$$D_b = e\left[\frac{-0.5K_d\rho_d DV_p wL_c}{(1-\beta)Q_r}\right] \quad (5)$$

All damaged and unthreshed grains were considered as a loss in the modelling of the total grain loss. This is because damaged grains may result in poor seed germination, and cracked kernels may result in dockage when sold for milling purposes. Furthermore, unthreshed heads retained for re-threshing often result in damaged kernels, and small kernel fragments resulting from damaged grain are likely to be lost totally during pneumatic separation. Therefore, the total grain loss in the threshing unit was presented as the sum of the threshing loss and grain damage loss.

The model used in calculating common beans thresher throughput capacity was expressed in Equation 6 (*Ndirika, 2006; Gregory, 1988; Vas and Harrison, 1969*), 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.

$$C_T = K_m Q_r Z\{1-\left\{\frac{\left[\lambda_1\lambda_3(\lambda_3-\lambda_1)e^{-\lambda_2 t_d}+\lambda_2\lambda_1(\lambda_1-\lambda_2)e^{-\lambda_3 t_d}+\lambda_2\lambda_3(\lambda_2-\lambda_3)e^{-\lambda_1 t_d}\right]}{\left[(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)(\lambda_3-\lambda_1)\right]}\right\}\} \tag{6}$$

1.2 Simulation of the performance of common beans thresher

In developing a simulation model, the best framework and language were chosen among the following: Visual Basic, web-based simulation model (Js), Matlab, and Python, among many others. The mathematical model equation were coded in the software, and to effectively manipulate the equations and computations, several dependencies using the pip command were installed. The user is requested to enter all the input parameters shown in Table 1-3. This is followed by a series of arithmetic manipulations.

Table 1

Fixed crop and machine input parameters into the model

Parameter	Dimensions
Radius of the driven pulley, Y	0.045 m
Mass of threshing cylinder, M_c	5 kg
Centre line distance between adjacent concave rods, a_1	0.04 m
Concave rod diameter, a_2	0.0018 m
Centre 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 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 (kg/s)	0.01, 0.02, 0.03, 0.04, 0.05
Peripheral velocity of the pegs, V_p (m/s)	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

Constants used in the applicable mathematical models

Constants	Values
Acceleration due gravity, g`	9.8
Slippage factor, K_a	0.35
Threshing constant, K_T	0.002
Damage constant, K_d	8×10^{-3}
Yield factor, K_m	0.7

1.3 Model testing and validation

Crop and machine parameters were entered individually and then simulated to view performance results. Parameters in Table 1 and 3 were kept constant, while those in Table 2 were varied to ascertain their effect on the thresher performance. A common beans thresher was then developed using design equations. Measured data from the developed thresher was used to validate the performance models by plotting graphs, student *t*-test, and residual analysis. The line of best fit, correlation coefficient, and coefficient of determination R^2 were used to measure how well the regression equation fits the 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 7 (*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 8, 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.

$$\varepsilon_r = \left| \frac{\psi_p - \psi_a}{\psi_a} \times 100 \right| \tag{7}$$

$$\eta_{um} = 100 \times \frac{\varsigma_w}{\varsigma_t} \tag{8}$$

RESULTS

2.1. Validation of simulated data

This study was meant to use a simulation method in the design of common beans thresher. This was intended to reduce the cost of design since most of the experiments are carried out on the model system and optimization. Therefore, the results from the model had to be verified with measured experimental data for validation purposes. The effect of peripheral speed on the performance of common beans thresher was carried out. The machine minimum drum speed was 400 RPM which was the start velocity for running loaded bean thresher. Based on preliminary experiments, any speed below the minimum could not operate the thresher with the load of unthreshed common beans. The maximum cylinder speed was identified to be 1200 RPM for purposes of safety and vibration of the machine. Therefore, at an interval of 100 RPM, the performance of the developed thresher using design equations was calculated from measured outputs. The same input parameters and variables used for the experimental thresher were fed into the simulation model that represents the common bean thresher. The output performance was calculated based on the developed model equations and recorded. The correlation coefficient of regression R, and the coefficient of determination R^2 were used to evaluate the relationship between the model and experimental results. The correlation coefficient numerically varies between -1 and 1, indicating negative, zero, or positive correlation between the model and measured results. Since the coefficient of determination must also have a statistical meaning, a statistical significance test at α = 5% was also done to ascertain how the sample data sets represent the whole population adequately.

2.1.1. Analysis of effect of pegs velocity on power required for threshing

The performance indicators for common thresher were power requirement, damaged grain, threshing efficiency, and throughput capacity. Figure 2 shows a comparison of experimental and computed power requirements for common beans thresher under different peripheral speeds of pegs.

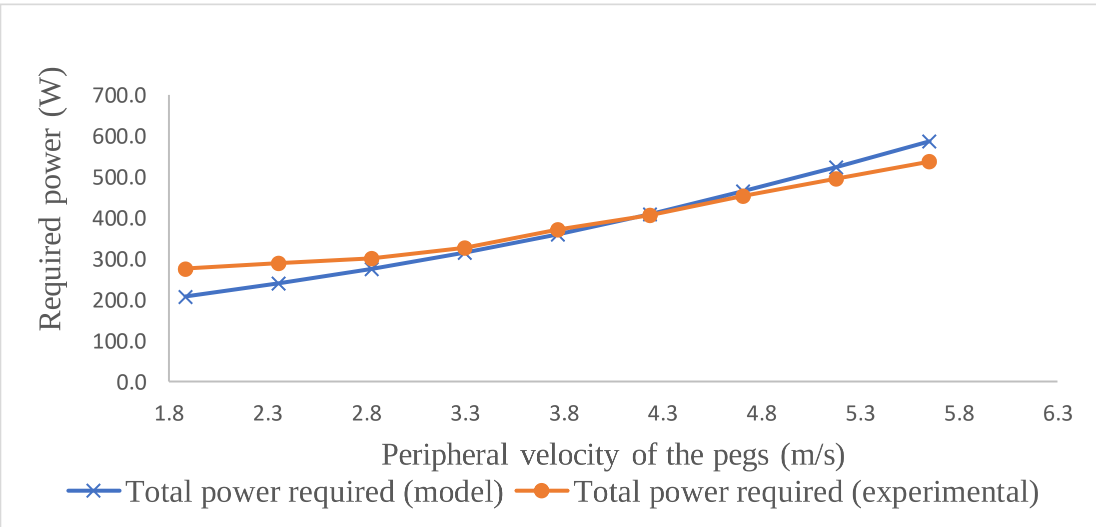

Fig. 2 - Comparison of experimental and computed power required for threshing common beans

Power required for threshing depends on detachment of the grain from the pod, frictional power, and power required to run the unloaded cylinder. As observed from Figure 2, there was an increase in power requirement for threshing common beans with an increase in peripheral velocity of the pegs in both the computed and experimental data. This is justified since power is mainly a function of velocity, cylinder revolution per minute, and cylinder mass. Therefore, increasing speed will result in increased power required for threshing. R^2 was 0.99 and 0.99 for experimental and computed power, respectively, required for threshing beans. This shows there is a positive correlation between the two data sets. Hence, the model can be used for simulating the power requirement for threshing. Similarly, when the student *t*-test for paired two sample means was conducted the t-statistics at 5% = 0.69 was less than t-critical = 1.89, a further indication that there was no statistically significant difference between the two data sets. This is also true because the computed data sets had a mean of 375.5 W power use within the speed range. In contrast, experimental results had a mean of 384 W. Generally, a farmer will prefer a machine with a low power requirement because of the reduced production cost.

The absolute residual error analysis (*Kanali, 1997*) between the simulated and the mean experimental observed power required for threshing for the 9 data ranged from 0.7% to 9.2%, with a mean value of 4.4%. This implies that there were discrepancies between the simulated and actual data on a few peripheral velocities of the pegs, which were slightly above the 5% residual error interval but on average, were within 10% residual error interval. This could be explained by the higher overall efficiency of the three-phase asynchronous motor than the single-phase used in the experimental thresher. At 10% absolute residual error interval, the prediction performance of the power requirement model was 78%.

2.1.2. Analysis of effect of pegs velocity on grain damage

Grain damage is a critical performance indicator for cereal thresher (*Osueke, 2014*). It has a direct effect on the germination of seeds and the market value of beans. In this case, it was determined by visual examination of any chipped, cracked or broken common beans grains expressed as a percentage of threshed bean grains. The extent and type of bean grain damage depend on machine and variety characteristics. The nature of damage experienced in large red kidney bean types during measured threshing was split into two halves due to impact action and rubbing against the concave surface. Figure 3 shows the results of measured and computed damaged grains of a bean thresher under different peripheral speeds of the peg.

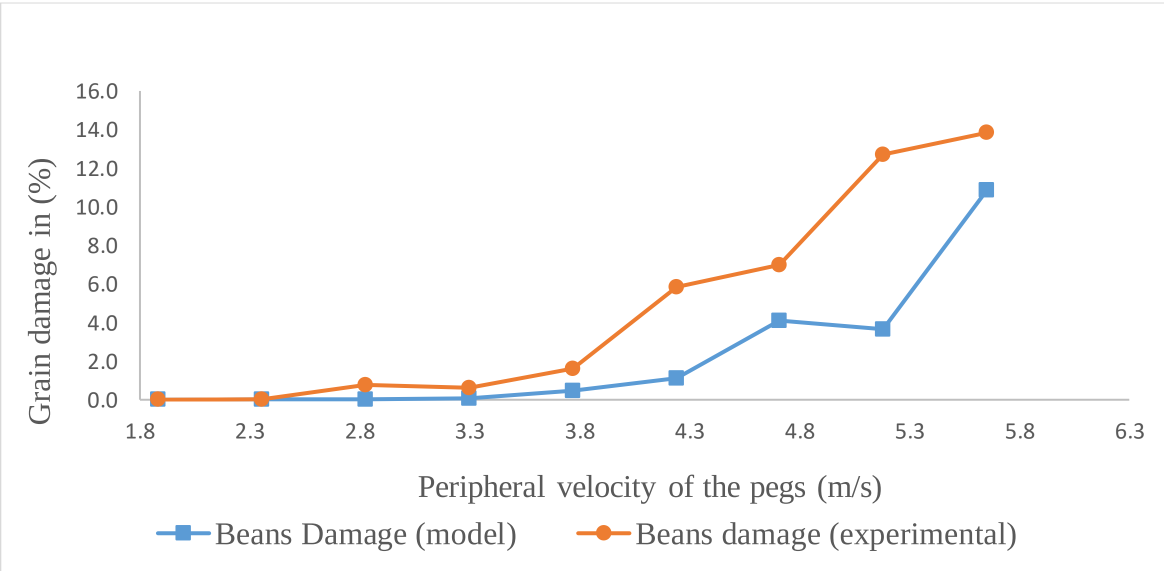

Fig. 3 - Measured and computed damaged grains of common beans thresher under different peg peripheral speeds

The computed damaged bean grains had a mean of 2.3% of threshed gains in all the evaluated peg peripheral speeds. This would be the ideal and recommended output for common bean thresher since the objective is to minimize grain damage. There was a slight increase of beans grain damage with an increase in peripheral velocity of the cylinder pegs. This was expected since an increase in cylinder pegs' peripheral velocity results in increased impact force enough to cause some grain damage.

The trend was different for experimental measured damaged bean grains under different cylinder speeds. The fraction of damaged grain was below 5% of threshed grain up to a maximum peg peripheral velocity of 3.8 ms^{-1} and increased drastically to 13.8% at a speed of 5.7 ms^{-1}. It was clear that at low speed, the damages were low since the impact force was low. The high bean grain damages at high speed for experimental thresher was a result of a design problem. The shape of the cylinder pegs needs to be smoothened instead of the bolts used, and sieve size increased to allow free fall of the beans grains through the concave surface. The absolute residual error analysis (*Kituu et al., 2010*) between the simulated and the mean experimental observed fraction of the damaged grains for the 9 data ranged from 0.2% to 18.6%, with a mean value of 7.2%. This implies some disparities between the simulated and actual data on a few peripheral velocities of the pegs, which were above 5% residual error interval but, on average, were within 10% residual error interval.

However, R^2 was 0.7 for the computed data sets, while the experimentally measured data was 0.8. This indicated a positive correlation between the computed and experimental beans grain damage during threshing. Since the bean grain damages that resulted from the simulation model were the expected outputs, it can therefore be used for simulation and optimization of common beans thresher. The student t-test was also conducted on the two sets of paired means, resulting in t_{stat}, 5% = 2.55 > $t_{critical}$ = 1.86, indicating that there was statistically significant difference between the two data sets. This was true because outliers occurred at high peg peripheral speed for the experimentally measured bean grain damage; otherwise, the trend of output values were almost the same. At a 10% residual error interval, the prediction performance of the damage model based on actual data was 77%.

2.1.3 Effect of peripheral pegs velocity on threshing efficiency

It was also important to determine the threshing efficiency for common bean thresher using computational mathematical model equations and experimental measured data. Threshing efficiency was determined as a fraction of threshed bean grains from the pods to the total sum of threshed and unthreshed bean grains expressed as a percentage. However, the total grain loss considers the sum of the total of damaged grains and threshing losses. Figure 4 shows the experimental and computed threshing efficiency of common beans thresher under different peg peripheral cylinder speeds. Common beans at moisture content less than 20% do not require much impact force for threshing. A little touch impact will break common beans pods, evident from the 100% efficiency results from experimental common beans thresher. At low peg peripheral speed tested between 1.8 and 2.8 ms^{-1}, the threshing efficiency of the measured thresher was a mean of 99%, after which a constant figure of 100% efficiency was maintained. This shows that during the operation of a beans thresher, the problem is not threshing instead, conveyance is the issue because of the long straws that wind on the drum cylinder (*Ukatu, 2006*).

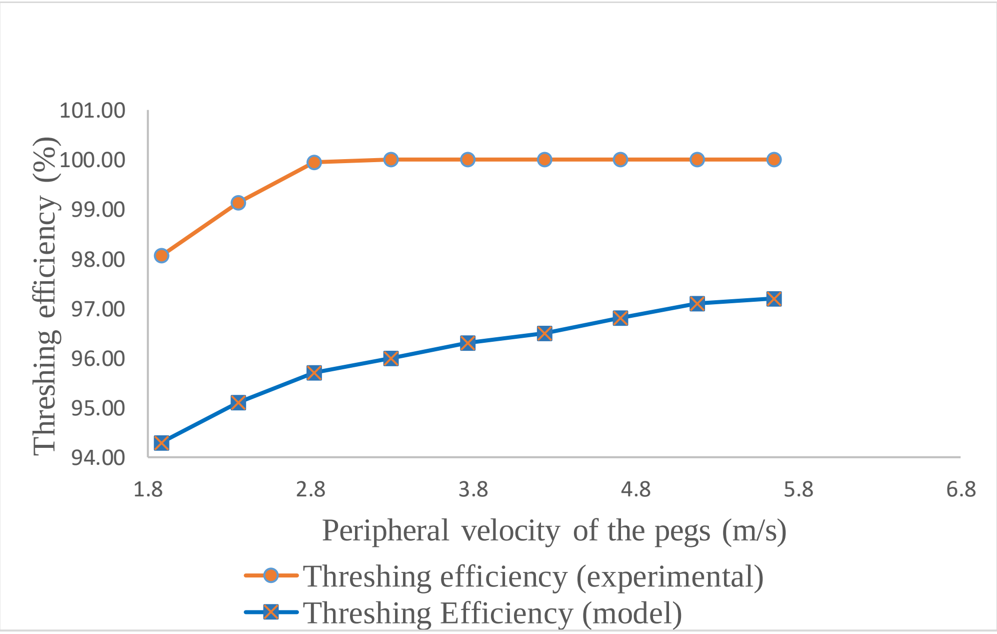

Fig. 4 - Comparison of experimental and computed threshing efficiency of beans thresher for different cylinder peg peripheral speeds

The average computed threshing efficiency was 96%. This is acceptable by many farmers for a thresher in the market (*Moussa, 2006*). There was an increase in threshing efficiency with an increase in peripheral velocity of the cylinder pegs for both experimental and computed output data. This is justified because threshing efficiency relates to the velocity of the pegs exponentially. R^2 was 0.91 and 0.5 for the computed and measured sets of data, respectively. Again this shows a positive correlation and the trend between the two sets of outputs from the model and experimental methods. Therefore, either of the two can be used for simulating the threshing efficiency of common beans thresher. However, there was a statistically significant difference between the two data sets since t-stat at 5% = 20.9 > t critical = 1.85. This could be explained by the little impact required for threshing dried common beans. The absolute residual error analysis results between the simulated and the mean experimental observed fraction of the damaged grains for the 9 data ranged from -2.8% to -4.5%, with a mean value of 3.5%. This implies some differences between the simulated and actual data on a number of peripheral velocities of the pegs, however, within -5% residual error interval. At 5% absolute residual error, the prediction performance of threshing efficiency based on actual data was 100%.

2.1.4 Effect of pegs velocity on throughput capacity

Processing time is of great essence in agricultural production, especially to get value for money from the produce. This can be significantly reduced by using machinery as opposed to hand working (*Ndirika, 2006*). Throughput capacity is an important output of a machine that influences the time of production. For common beans thresher, throughput capacity can be defined as the amount of threshed bean grains in an hour. 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. Figure 5 shows results of measured and computed throughput capacity of common beans thresher under different speeds of cylinder pegs. The trend from observation of Figure 5 was almost the same for computed and measured data sets.

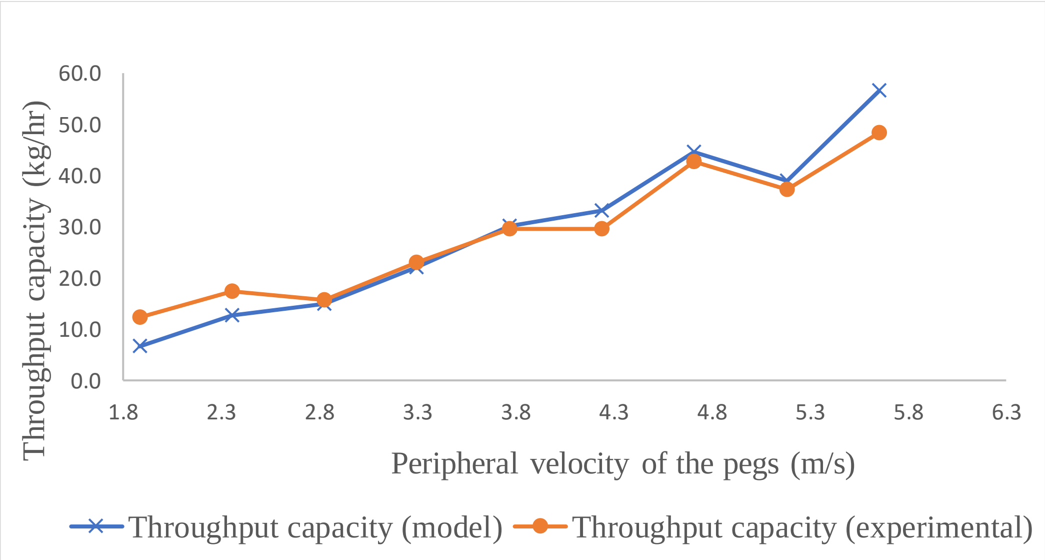

Fig. 5 - Comparison of computed with measured throughput capacity of common beans thresher under different peripheral speed of cylinder pegs

An increase in peripheral velocity of cylinder pegs resulted in increased throughput capacity. At high speed, the threshing process is faster, and the feeding rate is also enhanced. This is backed by the fact that the velocity of pegs, grain-straw ratio, bulk density, feed rate, separation efficiency, and concave configurations affect grain threshers' output capacity (*Behera et al., 1990; Enaburekhan, 1994; Ndirika, 1997*). This forms a good optimization criterion of maximizing the dependent variable based on independent variables, which can be achieved at low cost using simulation. R^2 was 0.99 for both computed and measured throughput capacity of common beans thresher. Again, this confirms a positive correlation between the simulated throughput capacity using mathematical models and the experimentally measured output capacity. Therefore, the model can be used for further simulation and optimization of the beans thresher. The student *t*-test was also conducted to check if there was significant difference between the two data sets. The t-stat at 5% = 0.29 < t-critical =1.89, an indication that there was no statistically significant difference among the two data set samples. Absolute residual error analysis was conducted, and the results between the simulated and the mean experimental observed fraction of the damaged grains for the 9 data ranged from 2.1% to 16%, with a mean value of 8%. This implies some disparities between the simulated and actual data on a few peripheral velocities of the pegs, which were above 5% residual error interval but on average were within 10% residual error interval. Based on the actual data and 10% absolute residual error interval, the prediction performance of the throughput capacity model was 77%.

2.1.5 Simulating the effect of moisture content on bean grain damage and threshing efficiency

While carrying out experiments to evaluate the performance of common beans thresher, grain damage at high peripheral peg speed was an issue of concern as opposed to threshing efficiency. Common beans threshability is high when the moisture content is low. The aim, therefore, is to minimize the fraction of damaged bean grain possibly to less than 2%. After validating a mathematical predicting equation for a performing common beans thresher, it was essential to simulate the effect of moisture content on performance.

The oven-drying method of moisture determination was used in calculating moisture content by wet basis for common beans. The moisture content was 56.7% and 46.6% for unthreshed common beans and bean grains, respectively, after harvesting from the farm. After sun drying, the moisture content by wet basis reduced to 18.7% and 17.6% for unthreshed common beans and bean grains, respectively, which was ideal for threshing using the developed common beans thresher. Using the same moisture content range, the performance of the bean thresher was simulated. Figure 6 shows the results of simulating the effect of moisture content on threshing efficiency and grain damage.

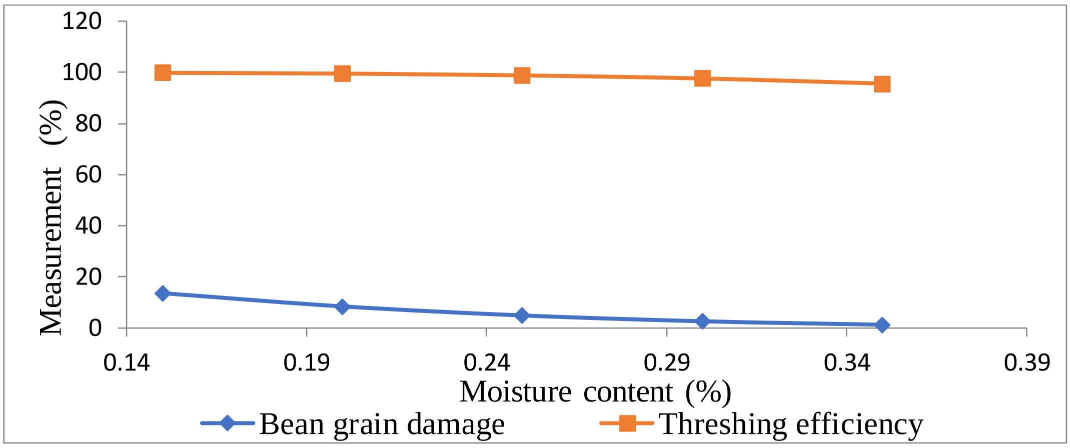

Fig. 6 - Effect of moisture content on threshing efficiency and grain damage of common beans thresher

The efficiency of threshing common beans decreased with an increase in moisture content of unthreshed beans as observed from Figure 6. The results are similar to *Osueke (2011),* which observed a decrease in threshing efficiency with increased 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. However, this is not effective at high moisture content. At a moisture content of 35% similar to that when harvesting, it can be observed that threshing efficiency will be at 95%, leading to high grain losses. Therefore, the recommended moisture content for threshing will be 20% and below.

Increased moisture content resulted in decreasing in damages of common bean grains. The results were similar to *Khazaei (2008)*, who found that increasing moisture content from 5 to 15% (wet basis), the mean values of the percentage of damaged beans decreased by 1.4 times. This could be because of the high threshability that exposes the bean grains to excess impact and rubbing action.

Therefore, optimization criteria will be to achieve high threshing efficiency with the lowest grain damages. Based on Figure 6, the recommended moisture content for threshing common beans will be 23% for low grain damage and high efficiency.

2.1.6. Simulating the effect of effective cylinder diameter on threshing efficiency and grain damage

Based on the cylinder-concave arrangement, an increase in effective diameter decreases the concave clearance. Therefore, concave clearance is inversely proportional to the effective diameter. To this extent, simulation of effective diameter results has a relationship with concave clearance. Figure 7 shows the results of simulating effective cylinder diameter on threshing efficiency and beans grain damage. It was observed that an increase in effective cylinder diameter results in increased threshing efficiency. This can be explained by the increased impact and rubbing action due to the reduced concave clearance leading to increased threshing. Similar results were discussed by *Osueke (2011)* based on published experimental data. He reported that decreasing the concave clearance resulted in increased efficiency. This was because decreasing concave clearance may have increased the chance of a grain being struck by the bar or spike and increased the chance of multiple impacts to the grain before it is passed from the threshing zone. The range of effective cylinder diameter of 0.2 m to 0.3 m was based on the spherical diameter of common beans, which was 0.16 m. The same interval was used during the experimental evaluation of the developed common beans thresher.

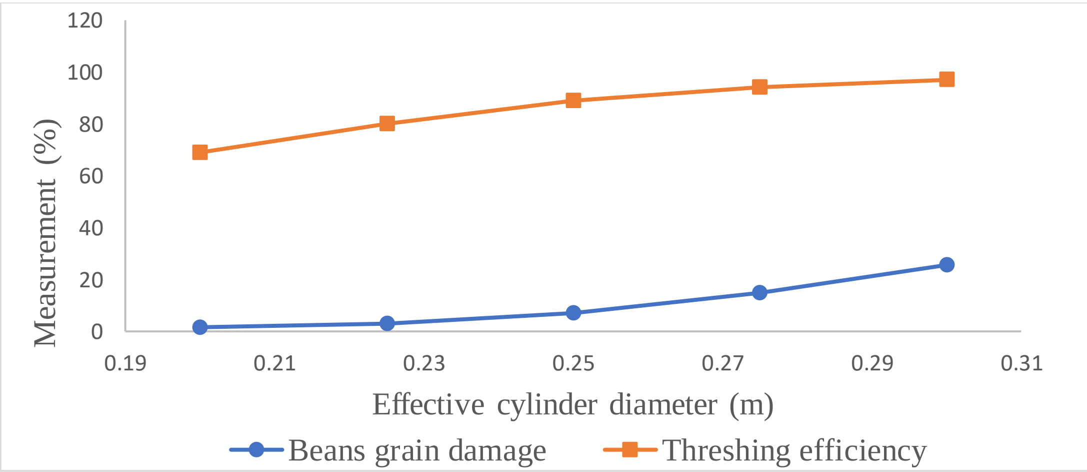

Fig. 7 - Simulation results of effect of effective cylinder diameter on threshing efficiency and bean grains damage.

An increase in effective diameter resulted in an increase in bean grains damage. The explanation for this is that rubbing and impact action was increased with reduced concave clearance leading to increased gain damage. Therefore, the choice of the correct effective diameter is very key in the reduction of grain damage. Optimization criteria are necessary to determine the correct cylinder-concave configuration (low seed damage) for effective germination of seeds and increased market value for the beans. This can be achieved by conducting experiments on the validated model system at low or zero cost.

2.2 Simulating the effect of concave width on threshing efficiency

During design, the determination of the correct and effective concave width is the key. Longer width of the concave calls for more materials, which has cost implications and makes the machine heavier for portability cases. Therefore, it was important to simulate the effect of linear concave width on threshing efficiency, as indicated in Figure 8. The 1 m span of linear concave width was divided into quarters of 0.25 m. The results from Figure 8 show that an increase in linear concave width resulted in increased threshing efficiency. This is justified by the increased exposure time of the unthreshed bean pods to impact, twisting, and rubbing action within the concave area. At a concave width of 0.25 m, the threshing efficiency was 25.4%, resulting in many losses. From the results, linear concave length less than 1 m gave an output threshing efficiency of less than 94.1%. This implies that for the design of a common bean thresher, the recommended linear concave width should be equal to or greater than 1 m.

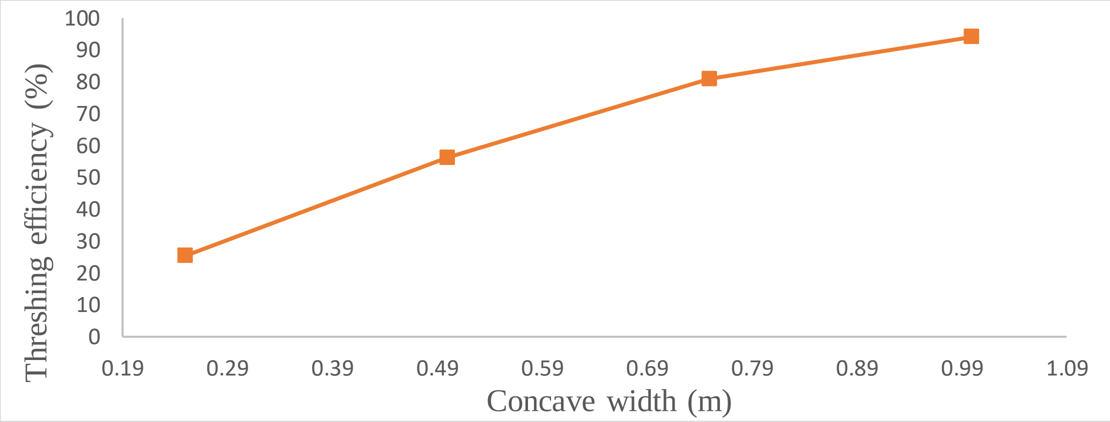

Fig. 8 - Simulation results for the effect of linear concave width on threshing efficiency

CONCLUSIONS

The goal of the study was to develop a common bean thresher by first simulating the design variables to understand the effect of independent and dependent variables on the performance of the thresher. The results then informed the sizing and design based on the correct cylinder-concave configurations, feed rate, peripheral speed of the pegs, moisture content, and bulk density of the unthreshed common beans. This is in relation to the performance of the developed thresher. The mathematical predicting equations for power requirement, bean grain losses, grain damages, efficiency, and throughput capacity were developed and validated using experimental data from the same study. The results showed a positive correlation based on the coefficient of determination for the used simulation models. Furthermore, the difference between the means of the computed and measured experimental outputs was not statistically significant at a 5% level of significance for all the performance models apart from the predicting damage equation. This gives a high confidence level to use the mathematical predicting equations for simulation and optimization of common bean thresher. The results noted that an increase in cylinder peripheral speed of the pegs increased power requirement, bean grain damages, threshing efficiency, and throughput capacity. In addition, the increase in the moisture content of beans resulted in a decrease in threshing efficiency and bean grain damages. The recommended moisture content for threshing common beans was 21% on a wet basis. Also, an increase in effective cylinder diameter caused an increase in threshing efficiency and grain damages. The spherical bean grain size is the determinant for the concave clearance size. Finally, an increase in linear concave width resulted in an increase in threshing efficiency. The recommended minimum width of 1 m can improve the threshing efficiency (94.1%) and thus avoid grain losses.

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