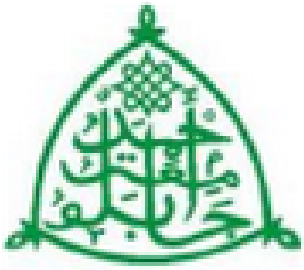

DEVELOPMENT OF MODELING SHELLING PARAMETERS AND OPTIMIZATION OF THE PERFORMANCE OF A STATIONARY IAR MAIZE DEHUSKER SHELLER

PhD RESEARCH THESIS

BY

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JULY, 2015

DEVELOPMENT OF MODELING SHELLING PARAMETERS AND OPTIMIZATION OF THE PERFORMANCE OF A STATIONARY IAR MAIZE DEHUSKER SHELLER

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DEPARTMENT OF AGRICULTURAL ENGINEERING
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AHMADU BELLO UNIVERSITY, ZARIA
NIGERIA

JULY, 2015

DECLARATION

I hereby declare that this dissertation entitled "Development of Modeling Shelling Parameters and Optimization of the Performance of a Stationary IAR Maize Dehusker Sheller" has been performed by me in the Department of Agricultural Engineering, Ahmadu Bello University, Zaria for the purpose of fulfilling the requirements for the award of Doctor of Philosophy (PhD) in Agricultural Engineering under the supervision of Professor D. D. Yusuf, Professor M. L. Suleiman and Dr. U. S. Muhammed. The information derived from the literature has been duly acknowledged in the text and a list of references provided.

_____ _____

Nalado Dauda Dangora Date

CERTIFICATION

This Dissertation entitled "Development of Modeling Shelling Parameters and Optimization of the Performance of a Stationary IAR Maize Dehusker Sheller" meets the regulations governing the award of the degree of Doctor of Philosophy of Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

_____ _____
Prof. D. D. Yusuf Date
Chairman, Supervisory Committee

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Prof. M. L. Suleiman Date
Member, Supervisory Committee

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Dr. U. S. Muhammed Date
Member, Supervisory Committee

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Prof. M. L. Suleiman Date
Head of Department

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Prof. Kabir Bala Date
Dean, School of Postgraduate Studies

DEDICATION

This work is dedicated to the Quds Martyrs, Sayyeds Ahmad, Hameed and Mahmoud Ibraheem El-Zakzaky (H). Their precious blood was extra judiciously and brutally shed by the Zionist dogs in the Nigerian military who act with impunity. These great martyrs sacrificed in the noble cause by expressing solidarity with oppressed peoples of the world especially the Palestinians. They were proactive in the struggle for revolutionary change of the contemporary tyrannical world order and for the growth of the Islamic Movement in Nigeria.

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All praise be to the Sustainer who instructs mankind to: “Read in the name of your Lord Who created. He created man from a clot. Read and your Lord is Most Honorable. Who taught (man to write) with the pen. Taught man what he knew not.” Peace and endless blessings be upon the best of all creatures Muhammad and his Progeny. I wish to express my thanks to Allah (T) who, in his infinite mercy, bestowed me with the intellect and ability to pursue this study. I wish to acknowledge the permission given to me by the Institute for Agricultural Research (IAR) Samaru, Zaria to use their Maize dehusker sheller for this study. I wish to express my profound gratitude to the chairman of my supervisory committee, Professor D. D. Yusuf who provided guidance, relevant materials and intellectual support for the overall success of this work. My thanks also go to my academic mentor Professor M. L. Suleiman. I would also wish to express my appreciation to Dr U.S. Muhammad. My special thanks go to Associate Professor M. K. Othman of NAERLS, Engr Muhammad Abubakar Funtua, Hajiya Binta Othman of the crop processing Laboratory and Jafaru Tanko of IAR, my skilled sheller operator. Baba Femi Amsain and Dr Attanda M.L. deserve special thanks for their respective valuable assistance to me.

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ABSTRACT

This study developed mathematical model parameters and optimized the performance of a maize dehusker sheller developed at the Institute for Agricultural Research (IAR), Ahmadu Bello University, Zaria. To facilitate this, a study on some physical properties of ACR, QPM and TZPB maize varieties in relation to moisture content was conducted. Three mathematical models for shelling, grain damage and scatter loss were developed based on dimensional analysis. All model development and validation were enhanced through performance evaluation experiments conducted with speed, feed rate, moisture content and cylinder concave clearance variables each at three levels in a completely randomized block design. The indices of model evaluation used were coefficient of determination, bias, root mean square error, index of agreement, slope and intercept of plots between the predicted values obtained from the developed models and the measured values obtained from experiments. Differential sensitivity coefficients were used to rank variables according to their order of importance in the developed models. SAS package was used for the statistical analysis of variance. Optimization based on genetic algorithm in MATLAB R2008a toolbox was used. Seven (7) functional parameters (input variables) under upper and lower constraints and three (3) performance criteria multi-objective output parameters were considered in the decision process in search of optimal solution. On the study of physical properties, analysis of variance showed that the effects of moisture content and maize grain variety were significant (at 5 %) for all the parameters considered. TZPB variety has the highest mean values of length, width thickness, one thousand grain mass and geometric mean diameter of 1.320 cm, 1.108 cm, 0.492 cm, 375.36 g and 0.896 cm, respectively, at 15 % moisture content, wet basis. The least was the ACR variety with 1.184 cm, 1.027 cm, 0.450 cm, 291.79 g and 0.818 cm respectively, for the parameters.

The highest mean value for the bulk density (876.40 kg/m^3), however, was obtained for ACR variety at 9 % moisture content, wet basis. As regards the dehusker- sheller performance evaluation studies, analysis of variance showed that all the four independent factors have significant effect on all the performance indices for both the model development and validation experiments. The model development mean results for output, shelling and cleaning efficiencies, grain damage and scatter loss were 609.55 kg/h, 98.06 %, and 87.12 %, 4.25 % and 14.08 % respectively. Validation mean results for those indices were respectively 578.26 kg/h, 98.18 % and 94.44 %, 3.97 % and 14.75 %. The different indices of model evaluation namely, bias, root mean square error, index of agreement, square bias and coefficient of determination, between the predicted values and the measured values were: 0.314, 0.194, 0.974, 0.073 and 0.937, respectively for shelling; 0.453, 0.121, 0.907, 0.0144 and 0.901, respectively for grain damage and 1.462, 1.262, 0.629, 1.587 and 0.733, respectively, for grain loss. These show that there was significantly good agreement between the predicted and the measured values. The genetic algorithm optimal values of the input variables were 641.86 kgm^{-3}, 0.617 kgs^{-1}, 0.179 m, 8.70 ms^{-1}, 0.04 m, 10.4 %, and 0.775 m for maize bulk density, feed rate, cylinder drum diameter, cylinder speed, cylinder-concave clearance, grain moisture content (wet basis) and shelling length, respectively. The optimum performance parameters obtained were 99.18 %, 4.23 % and 6.31 % for shelling efficiency, grain damage and grain loss, respectively. Thus parameters for an optimized sheller with maximized shelling and minimized damages and losses have been established.

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LIST OF SYMBOLS

β_1 = A constant separation co-efficient

s_s = the cumulative separation function (in decimal)

r_s = the remaining grain to be separated, %

λ_v = Wacker coefficient for threshing zone

β_q = Wacker coefficient for separation zone

F_{mog} = Material other than grain (MOG) throughput, kgs^{-1}

V= rotor (cylinder) speed, ms^{-1}

m_g = total grain mass, kg

F_g = Fraction of grain lost due to incomplete threshing

$\gamma =$ straw to grain ratio

P = power required, W

N = rpm of rotor

F_q= Gregory feed rate, kgs^{-1}

λ_0 = coefficient of threshing units

λ_1 =coefficient of crop properties

s_n = mass of Unthreshed grain, kg

λ_s = shelling rate, m^{-1}

λ_D = grain damage rate, m^{-1}

β_s = shelling separation rate, m^{-1}

λ_t = mean threshing rate, t^{-1}

t_c = dwell time, s

λ = specific threshing rate, m^{-1}

β = specific separation rate, m^{-1}

V_t = threshing loss, %

k_t = threshing constant

F_r = crop feed rate, kgs^{-1}

C = concave clearance, m

ρ_g = grain bulk density, kg m^{-3}

ρ_s = straw bulk density, kg m^{-3}

M_s = straw moisture content, %

M = grain moisture content, %

η_c = cleaning efficiency, %

η_s = shelling efficiency, %

k = component equation constant

D = cylinder drum diameter, m

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Less than a dozen plant species provide over 80 % of mankind's diet, and among these plants, the cereal crops are in the first place (Kim and Gregory, 1989a, b). Maize is a crop per excellence for food, feed and industrial utilization (plate I). Maize is the third most important crop in the world after wheat and rice (Adebayo *et al.*, 2010). Worldwide production of maize as at 2008 was 785 million tons with Africa producing 6.5 % and the largest producer is Nigeria with nearly 8 million tons (IITA, 2009). World cereal **production** in 2014 is anticipated to reach 2, 523 million tons, some 65 million tons higher than FAO's initial forecast published. A continued upgrading of coarse grain harvests, maize in particular, has been the main underlying factor (FAO, 2014). Maize is presently the most important cereal crop in West and Central Africa because of its high yield potential, increasing role in the human diet, its use for animal feed and in agro allied industries (Baffour *et al.*, 2014). Of all the important cereals, maize remains the most popularly grown and consumed across a range of ecological zones of Nigeria (Iken *et al.*, 2002; Baffour *et al.*, 2014). Maize has a relatively short growing period. It is easy to grow, process, store and market. It is well integrated into the farming system. It is now cultivated in the drier areas. It has added potential for addressing the food security challenges presently faced in West and Central Africa as a result of increasing effects of urbanization. (Baffour *et al.*, 2014). Nutritionally, it has high content of carbohydrates, lower fats, proteins and some important vitamins and minerals (Punita, 2006).

Plate I: *Zea mays L.* : Cob and Plant (*Source*: Gopalan, *et al*., 2007).

On average, about 70-75 % of the kernels, depending on the type, composed of carbohydrate which is mainly present as starch and sugar (Baffour *et al.*, 2014). Maize accounts for 15-20 % of the total daily calories in the diets of people in more than 20 developing countries mainly Latin America and Africa. In the developed countries such as United States (USA) and Europe, it is an important feed grain for livestock and poultry because of more efficient conversion of its dry substance to meat, milk and eggs. USA approximately converts 60 % of its maize crop to animal feed (Pingali and Pandey, 2000). The major varieties of corn are pod, flint, sweet, pop, floury and waxy (Staachmann and Matz, 1977). Carotenoids, which are precursors of vitamin A are present in yellow types but absent in white maize. The quality of the protein is considered poor because the kernels have low content of lysine and tryptopan - two of essential amino acids. Years of research have resulted in the development of quality protein maize, QPM, which contains twice the quantity of lysine and tryptopan in the normal maize (Twumasi-Afriye *et al.*, 1999).

Local demands for threshing equipment have encouraged unprecedented production of power threshers in many developing countries. Threshers have proven to be precursor to mechanization and a needed item that can launch indigenous manufacturing capabilities in low income countries (Kutzbach and Quick, 1999). Threshing is the first and most important postharvest operation for grain crops. It involves, among other things, the detachment of grain kernels from the heads, cobs or pods as the case may be. Traditional methods are laborious, the output is low and high losses are also recorded (Enaburekan, 1994). The output in terms of dehusking-shelling of Maize cobs was reported to be 30 kg/hr with 8.3 % grain damage in the traditional system - dehusking by hand and beating with wooden sticks (Singh *et al.*, 2011).

Mechanical or power threshers have been introduced and are popular in most developing countries to overcome those difficulties (Enaburekan, 1994). The ideal threshing unit (processor) is the one that produces a perfect threshing of maximum crop throughput with optimum grain separation, while it preserves the natural shape and quality of the grain and minimize grain loss (Miu, 1995, Miu and Kutzbach, 2000). Threshing, as it applies to maize crop, is commonly referred to as shelling. In some sheller designs, the husks have to be separately removed before feeding, whereas in others, the whole head including the husks are fed into the sheller. These are referred to as dehusker shellers. In order to design equipment for handling, conveying, separating, drying, aeration, storing and processing of maize seeds, it is necessary to know the crop and machine factors that play key roles in their optimal performance. The crop factors, machine parameters and their interaction determine the performance characteristics of a particular threshing machine (Enaburekan, 1994). The purpose of modeling a physical system is to be able to better understand the fundamental mechanism of that system and to establish the optimum conditions for the design, construction and operation of the system. Optimum conditions are those that produce the most favourable or most beneficial result from a system (Gajda and Biles, 1978).

1.2 The Existing IAR Maize Dehusker Sheller

This machine uses a peg type cylinder, which works against a stationary concave screen. The drum is mounted on a 28 mm diameter shaft. The pegs are arranged in four rows with each row having five pegs. The cylindrical pegs have a uniform height of 48.5 mm above the drum. The prime mover is a 4.5 kW diesel engine. The machine does not incorporate a reciprocating sieve assembly. The cylinder-concave clearance is 40 mm (see plate II and Appendix VI- Drawings). There are no concave bars as in other threshers considered by Enaburekan (1994) and Ndirika (1997). Also a cob thrower outlet is provided at the end of the shelling length. Sieve hole openings are 21 mm in diameter and have a distance of 50 mm centre to centre.

Plate II: The Existing IAR maize Dehusker Sheller

1.3 Statement of the Problem

Maize (*Zea mays L.*) is the preferred staple food of more than 1.2 billion consumers in Latin America and sub Saharan Africa, where 30 – 50 % of the population is malnourished (Sobukola *et al*., 2008). Studies in Maize production in different parts of the country (Nigeria) have shown an increasing importance of the crop amidst growing utilization by food processing and livestock feed industries (Ogunsumi *et al*., 2005).Over the years, different mechanical means of shelling were introduced into Nigeria. Power operated threshers of various models exist in the Nigerian market (Ali, 1999). The crop factors, machine parameters and their interaction determine the performance characteristics of a particular threshing machine (Enaburekan, 1994). The purpose of modeling a physical system is to be able to better understand the fundamental mechanism of that system and to establish the optimum conditions for the design, construction and operation of the system. Optimum conditions are those that produce the most favourable or most beneficial result from a system (Gajda and Biles, 1978). However, various evaluation tests conducted at the Institute for Agricultural Research (IAR), Ahmadu Bello University, Zaria, revealed various defects in the performance of these machines. Seed losses were of unacceptable limits (>5%). Cleaning efficiencies were unsatisfactory in most cases (IAR, 1994). This was among the reason that prompted the Institute's drive in the development of prototype equipment that would suit Nigerian condition.

It was in this context that the IAR developed a maize dehusker sheller. The machine has, over the years, undergone modifications to improve on its performance. Currently, the machine has wide patronage by farmers in the North Western states of Nigeria (IAR

mandate states). Most farmers in developing countries possess farmlands less than 5 hectares (Singhal and Thiestein, 1987). This makes the practice of mixed cropping popular. This reason, among others, prompted the farmers in the IAR mandate states to recommend the modification of this rugged sheller for threshing of their additional commonly grown crops such as sorghum, millet and cowpea. Nalado (2007) evaluated and modified the sheller for multi-crop threshing. It was however observed that the maize grain losses, more especially from the cob thrower outlet, are above acceptable limits (>12 %). Thus it was recommended that mathematical models should be developed to be used in predicting sheller performance and to optimize the dehusking-shelling process of the machine for minimum scatter losses.

1.4 Justification

In Nigeria, there are some works on thresher design, modification, improvements and evaluation (Akubuo, 2002, Ahaneku *et al*., 2003,). However, limited works are reported on modeling of power operated threshers. This provides a strong motivating factor for this work. The mathematical modeling and optimization would provide for a comprehensive understanding of fundamental relationships of the shelling processes. Non measurable dynamic process parameters could be reasonably quantified. It would also be used to predict unit performance over a large range of parameter variation. The models would serve as programming keys for dynamic process simulation and optimization. This would then be used as bases for design and selection of functional parameters of the working machine. A very important outcome of the modeling and optimization would be the minimization of maize grain losses. The advancement of computer technology coupled

with the availability of simulation and optimization packages have made it possible to develop a fundamental theory for prediction purposes (Yusuf, 2001) which include shelling process of maize dehusker sheller. Description of this process through this approach is based upon the advantages of mathematical models which promote understanding of the important process mechanisms.Modeling and optimization would improve on the farmers' satisfaction because of obvious reasons such as more efficient machine performance and reduced operational costs and time. It would pave way for the growing processing industries to get their needs as appropriate. All these are part of the efforts that would help towards achieving the goals of agricultural mechanization in this part of the country and in the whole country in general.

1.5 Objectives of the Study

The aim of this study was to develop models and optimize the performance of a power operated stationary IAR maize dehusker sheller.

The specific objectives of the study are:

i. To determine some physical properties of ACR,QPM and TZPB varieties of *Zea mays L*
ii. To conduct performance evaluation of the developed IAR maize dehusker sheller for model development and validation.
iii. To develop and validate mathematical models for prediction of the sheller performance
iv. To optimize the sheller performance parameters

1.6 Scope and Limitations of the Study

The crop physical properties obtained were limited to only three varieties of *Zea mays L* (ACR, TZPB and QPM) considered within three moisture regimes (9, 12 and 15 %, wet basis). The universal mathematical model of grain threshing and separation (which is applicable to both tangential and axial feeding) as developed by Miu, (1995) and validated by (Miu and Kutzback, 2008) was used. However, this work was limited to stationary power threshers. The study considered speed and feed rate as the machine operational factors. Concave clearance and drum diameter were considered as machine design factors. Other design factors such as beater peg diameter and concave hole configuration were not considered. Other aerodynamic factors such as fan speed, drag coefficients were also not considered in this work.

2.0 LITERATURE REVIEW

2.1 Introduction

Development of Power Threshers as Precursors of Mechanization, the crop physical properties influencing threshability, the criteria for evaluating threshing performance, the effects of crop and machine parameters on threshing performance and the previous results of studies on mathematical modeling and optimization of grain threshing and separation processes are all discussed in this chapter. Different approaches in the published theories have been presented and assessed. Much experimental work has been carried out on threshing units and much effort has been extended in the analysis of the results. Different approaches have been used in literature.

2.2 Development of Power Threshers

Power threshers played an important role as the forerunners of farm mechanization in the Western world. The same was true of Japan and is proving to be the case yet again in nations of the developing world. Threshers progressed from hand-feed to mechanical head-feed and from stationary to self-mobile machines (Kutzbach and Quick, 1999). Western-style or even modern, small Japanese combine harvesters have been shunned by low-income farmers with fields that are often too small or inaccessible for self driven equipment. Manual threshing is probably the most tedious and least-attractive field activity. Rising labor costs and manpower scarcities for harvesting accordingly have hastened the development of a wide range of power thresher designs across the rice world in the last 40 years (Kutzbach and Quick, 1999). In some low-income parts of Africa,

Latin America and Asian nations, labor costs are still relatively cheap enough that the use of the sickle and manual threshing still predominates. But in these places the use of the power thresher is the necessary first step to enhance labour productivity and reduce drudgery in what may be referred to as labour-intensive mechanization. Many thresher designs have been manufactured in China, such as conical throw-in threshers, twin-drum through-flow types, vertical-shaft as well as horizontal axial-flow and fan-type power threshers. The Chinese have introduced rural electrification to an extent unprecedented in history. It is not uncommon to see in remote fields, far from any buildings, a thresher brigade manhandling their sled-mounted thresher with its electric motor over to a power pole socket connected to the overhead power line. (Kutzbach and Quick, 1999). Stationary power threshers are completely outdated in the industrialized Western World. By contrast, in developing countries, there are places where threshing is still done using muscle power. Hand or foot treading, either human or animal, or manual bundle-beating still goes on. Imported threshers were and are still tried in Nigeria, but they were just too costly, ill-suited to small or inaccessible fields coupled with dismal performance in many cases. This has made indigenous thresher development in particular and indigenous development of other farm machinery in general, imperative. The Institute for Agricultural Research, IAR, Ahmadu Bello University, Zaria, Nigeria and indeed some other Research and professional Institutions, have made some advances in these direction.

2.3 Maize Processing

Harvesting and threshing of maize pose a major challenge in Nigeria, particularly with the increase in production of the crop. The shelling process depends on the maize variety characteristics, the design and structure of the threshing apparatus, and its adjustment. Most low acreage farmers, who grow maize in Nigeria, encounter several processing difficulties of which shelling, as it requires a relatively high expenditure of energy, is a major concern (Adewunmi, 2004). The most important quality indices for maize ears threshing are grain loss, damage, concave separation, and the degree of the ear length reduction. The threshing process depends on the maize variety characteristics, the design and structure of the threshing apparatus, and its adjustment (Petkevichius *et al*., 2008). Kravchenko and Kuceev (1979) determined that adhesion between a grain and the maize cob depends on the grain moisture content and its location on the ear. At the ear base kernel attachment is the strongest and at the top it is the weakest. As grains dry, their adhesion to the cob increases. In order to detach grains from the cob some force should be applied longitudinal or perpendicular to the ear axis (Kravchenko and Kurasov, 1988). When threshing the ears approximately 66 % of power is used to overcome the friction forces between the grains and only 34% of power is used for the ear deformation (Kurasov and Kuceev, 1999). The main influences on maize threshing are the gap between drum rasp bars and the concave and the drum peripheral velocity. Kravchenko and Kuceev (1987) found that the optimum speed of the threshing drum rasp bar was $11ms^{-1}$. This was about 2.5 times less than the movement speed of the rasp bars when the grain crops were being threshed (Gasparetto *et al*., 1989).

Most investigations of the threshing of ears with medium moisture content concentrate on grain damage. Wacker (2005) found that the least maize grain damage (11%) occurred when the moisture content was 28% wet basis. On threshing of maize grains on 41% moisture wet basis, grain damage increased to 33%.Wacker (1987) also stated that grain damage from an axial threshing machine is less than that of a tangential machine. Data obtained by Vindizhev and Blaev (1983) showed that maize grain damage occurred when the drum rasp bars operated at a rate of $7ms^{-1}$ and their impact direction coincided with the longitudinal axis of a grain. When the impact direction is at an angle with the grain longitudinal axis, the damage appears at rasp bar speeds of $15ms^{-1.}$. During the harvesting of maize the number of ears fed to the threshing drum varies considerably. Kustermann (1987) states that during the first impact of the rasp bar the greatest number of grain are threshed. The degree of grain threshing depends on the ear orientation with respect to the drum shaft position (Kuceev, 2000).

When the ear axis is parallel to the drum shaft grain threshing losses are 2.3 times lower than in case of threshing when the ears fed perpendicular to the drum shaft. Most researches into maize threshing have evaluated the ear threshing process with respect to grain damage and grain losses during threshing. However, the reasons for grain damage or loss during the threshing do not often evaluate the movement of ears in the threshing apparatus. Crop movement in the threshing apparatus was investigated by Gasparetto *et al*., (1989), who found that the threshed dry ear in the concave move 4 times slower than the threshing drum rasp bars and that the threshed grains move in several directions in the threshing apparatus. The threshing of ears with moisture content greater than 30% has not

been fully investigated because grain moisture should be less than 30% when maize ears are harvested for storage. Rotary threshing units in which the crop is fed axially or tangentially into the rotor are becoming more popular (Kutzbach and Quick, 1999). There are different threshing cylinder configurations. Figure 2.1 shows the common types.

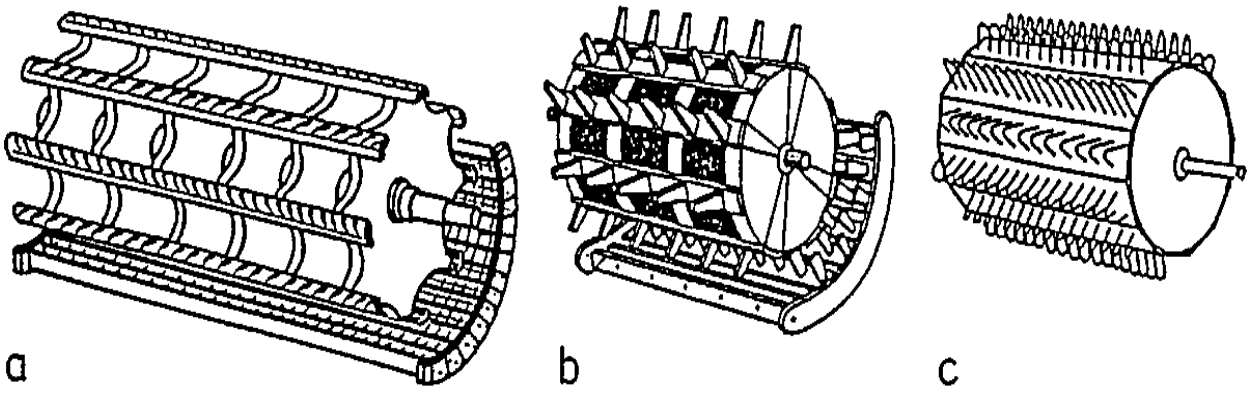

Figure 2.1: Threshing Cylinders: a) rasp-bar; b) spike-tooth; c) wire-loop
(Source : *Kutzbach and Quick, 1999)*

The simplest arrangement is the one with wire loops on its periphery. Grains are combed out easily while a handful of material is held against the wire loops of the revolving cylinder.

2.4 Criteria for Evaluating Threshing Performance

From available literature (Enaburekan, 1994; FAO, 1994; Behera *et al*., 1995; Ndirika, 1997; Ahaneku, *et al*., 2003; Simonyan 2006), the criteria for evaluating the performance of threshing mechanisms include threshing efficiency, grain loss, grain damage, output Capacity, cleaning efficiency, power requirement and threshing recovery. These criteria are measured against some variables namely: crop moisture content, cylinder threshing speed, crop feed rate, concave clearance, cylinder diameter and threshing length. The grain output capacity, expressed in Kg/hr, is the amount of grain threshed per unit time. The threshing efficiency is the quantity of threshed grain in the sample per unit time to the total grains in the sample expressed as a percentage. Grain damage is the percentage of visually broken, chipped or cracked grain to the total grains that have been threshed per unit time. Grain loss, expressed as percentage, is the amount of grain that has not been collected at the designated output compared to the total grains threshed per unit time. Some authors (Enaburekan, 1994; Ndirika, 1997) considered total grain loss as a summation of the grain loss as defined above and the one due to damage.

2.5 Effects of Crop and Machine Parameters on Performance

The crop parameters which are of importance include the moisture content, the biometric properties such as size of the grain, grain - spent cob ratio, grain bulk density, sphericity, angle of repose, terminal velocity, one thousand grain mass and porosity. For processing of maize seeds in general and threshing in particular, it is necessary to determine some physical properties, which in most cases, are dependent on the moisture content. These properties include dimensions (size, shape), bulk density, porosity, coefficient of static friction, volume, weight, specific gravity, density, porosity, surface area, angle of repose and angle of internal friction; Many Scientists (Mohsenin, 1970; Waziri and Mittal,1983; Deshpande *et al.*,1993; Joshi *et al.*,1993; Gupta and Das, 1997; Nimkar and Chattapadhyay, 2001; Isiaka et al., 2006;) have pointed out their practical utility in machine and structural design processes and control engineering. Physical properties of agricultural products are studied by considering them individually because of their irregular shape and variability in size. Hence, it is important to have an accurate estimate by using suitable methods for various classes of biomaterials. Physical characteristics of food grain are important in association with the design of a machine or analysis of the behavior of the product in terms of handling and storage and in the development of new consumer products (Gadang *et al*., 2006). Determination of physical properties as a function of machine are important to design equipment for handling, conveying separation, drying, aeration, storage and processing . The size and shape are for instance important in their separation from undesirable materials and in the development of sizing and grading machinery (Sobukola *et al*., 2013).

Sobukola *et al*., (2008) found out that linear dimensions, one thousand seed mass, sphericity and coefficient of static friction increased linearly with increase in moisture content. Bulk density, true density and porosity were observed to decrease linearly as moisture increases. The Angle-of-repose increases logarithmically with increase in moisture. Soliman and Korayem (1983) and Mohsenin (1986) demonstrated several statistical regression equations to determine the values of different physical characteristics of some grains, beans and fruit as a function of moisture content. Matoukk *et al.* (2004) studied the effect of machine on physical characteristics of some grains at a range of 10-26 % moisture content (wet basis). They concluded that a positive relationship was found between moisture and each of the weight of 1000 grain and grain projection area while a negative relation was found with shape index and coefficient of surface contact (Soliman and Abdulmaqsud (2007).

According to Kaul and Egbo (1985), the performance of a thresher depends upon its size, cylinder speed, cylinder concave clearance, fan speed and the sieve shaker speed. The pertinent machine parameters affecting design, performance and evaluation of shellers include the cylinder type, feed rate, the concave length, the concave clearance, concave hole size, fan (air) speed, sieve oscillation frequency and the cylinder peripheral velocity (drum speed), among others (Enaburekhan,1994; Simonyan, 2006). Oni and Ali (1986) reported that the factors influencing threshability of maize in Nigeria are field drying, maize varieties, ear size, cylinder speed and feed rate. The properties of the crop that affect the thresher performance are crop variety, shape and size, hardness of the seed, the moisture

content of the seed and the density. They also noted that overall threshing efficiency was influenced by cylinder speed, crop ear size and two factor interaction (speed x variety) and (feed rate x ear size). In all cases, the higher the speed, the higher the rate of shelling at the moisture levels evaluated. They found out that the shelling rate, however, decreased with an increase in moisture content of the grain. In addition, they also observed that the higher the speed, the more the grain damage. Sudgan *et al*. (2005) found that the concave clearance and the drum speed significantly (at 1 % level) affected output capacity. They found out that the percentage grain damage increased with an increase in drum speed and it decreased with an increase in concave clearance. Sseiz *et al*., (2007) found that speed and feed rate have significant effect ($pr < 0.01$) on power requirement. Power requirement increased with increasing feed rate and drum speed. Increased drum peripheral velocity improved the threshing efficiency. Vajasit and Solokha (2006) showed that the output capacity rapidly increased with an increase in drum speed for all feed rates and grain moisture content. Maximum capacity was obtained at the highest feed rate. Also as the feed rate was increased capacity increased at all drum speeds and moisture content. At all feed rates and drum speeds, the capacity slightly decreased as the moisture decreased. Their Analysis of variance shows that the main effects of speed, feed rate and moisture content were highly significant on capacity. Analysis of variance on the main effects of moisture content, feed rate and speed show significant effects on grain damage (1 % level), threshing efficiency and grain loss (Vajasit and Solokha 2006). Furthermore they indicated that the grain loss increased with an increase in grain moisture at all levels of feed rate.

The threshing efficiency of the Soyabean threshing mechanism developed by Fernando *et al*., (2004) differed significantly with shaft rotational speed. Seed breakage and seed coat damage increased with increasing shaft rotational speed of the threshing mechanism. El-Haddad (2000) stated that the threshing efficiency increased with increasing of drum speed and decreasing of feed rate. El-Behiry *et al*., (1997) found that the feeding rate increasing linearly by increasing drum speed. The straw sizes decreased by increasing the drum speed, while the grain losses increase. Also, the straw sizes decreased at lowest moisture content under all threshing process. Huynh *et al*. (1982) stated that the seed separation from the stalks and passage of seed through the concave gate was a function of some variables such as crop feed rate, cylinder speed, concave length and cylinder diameter and cylinder concave clearance. These variables are also related to the threshing losses and seed separation efficiency. El-Banna (1979) indicated that the useful horsepower required to thresh wheat is mainly affected by cylinder speed and depends on feed rate and more power would be consumed with higher feed rates. The unthreshed grain losses decreased with increasing the cylinder speed and decreasing the feed rate. Anwar *et al*., (1991) concluded that the cleaning efficiency increased with increasing cylinder speed and decreased with increasing feed rate.

Elsaeid *et al*.(2009) introduced new combine threshing rotor designed to improve threshing process and increase the field capacity, in addition to maintain a non harmful low noise level effect on the environment. Chuan-udom and Chinsuwan (2009),

conducted a study on the threshing unit loss prediction for Thai axial flow rice combine harvesters. They derived prediction equations with a correlation coefficient ($R^{2)}$ value of 0.92 and an average error value of 0.10%. Junsiri and Chinsuwan (2009) predicted header losses of a combine harvester when harvesting Thai Hom Mali rice.The results of the study stated that grain moisture content (M), reel index (RI), cutter bar speed (V_{cb}), service life of cutterbar (Y), tine spacing (R), tine clearance over cutter bar (C), stem length (H), product of M and Y (M*Y), product of M and V (M* V_{cb}), product of RI and R (RI*R), product of V_{cb} and C (V_{cb} *C), product of V_{cb} and H (V*H), V_{cb}^{2} and RI^{2} were the major parameters affecting the losses. The prediction equations had a correlation coefficient (R^{2}) of 0.75. The average percentage header losses given by the estimation equation differed from the actual field measurement by 0.25. Andrews *et al.* (1993) studied the effects of the operating parameters of combine harvesters on harvest losses of rice by forming a process equation and calculating their losses from the rice combine harvesters by using a second order response surface model. The findings reported that the feed rate, ratio of grain to material other than grain, moisture content, rotor speed and concave clearance affected threshing losses. Craessaertsa *et al.* (2007) established a non-linear prediction model for the material other than grain (MOG) content in the grain bin by means of fuzzy modeling techniques.

2.6 The Modeling Process

Mathematical modeling describes the process of obtaining a solution to a real world problem. Many real problems can be very complex and so the idea of creating a mathematical model is to simplify the real situation. These mathematical models can provide solutions to the original problem. It is often necessary to interpret these answers in the context of the original problem and to check that the answers that you have obtained are reasonable (Velten, 2009).

2.6.1 General threshing models

Simple models use a single exponential function that represents the cumulative separation function s_s for an axial threshing unit (Wacker, 1985) as given in equations 2.1 and 2.2

$$s_s(x) = 1 - e^{-\beta_1 x} \quad (2.1)$$

$$r_{s(x)=}\ e^{\beta_1 x} \quad (2.2)$$

Where, S_S is the cumulative separation function (in decimal), r_s is the remaining grain to be separated, %, β_1 is a constant separation co-efficient, i.e., threshing and separation processes occur simultaneously over the threshing length. These models offer the advantage of simple calculations with variable accuracy depending on the current position *x* within the threshing length. A single separation coefficient cannot incorporate all influences of unit design specifications and functional parameters. The coefficients for threshing, segregation, and separation operations are embedded within the separation coefficient. Furthermore, Wacker (1985) proposed two different coefficients, λ_v and β_q, for threshing and separating zones, respectively. Moreover, he found that second order

polynomials could quantify the influence of rotor speed, v and MOG throughput, F_{mog} on the separation coefficients as follows:

$$\lambda_v = a_v + b_v v + c_v v^2 \quad (2.3)$$

$$\beta_q = a_q + b_q F_{mog} + c_q F_{mog}^{\ 2} \quad (2.4)$$

where *a*, *b*, and *c* are experimental coefficients that depend on material properties and threshing unit design. Caspers (1973) developed an exponential function with a third degree polynomial exponent as follows:

$$Ss = m_g\,(1 - e^{-(a_1 x + a_2 x^2 + a_3 x^3)} \quad (2.5)$$

Where m_g = total grain mass; $a_1, a_2\, a_3$ are coefficients that depend on unit design and material properties. For grain separation in a tangential unit, Lo (1978) developed an exponential function whose exponent is expressed as a fourth degree polynomial of threshing length:

$$Ss = m_g\,(1 - e^{-(a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4)} \quad (2.6)$$

A single separation coefficient cannot incorporate all influences of unit design specification and functional parameters. The coefficients of threshing segregation and separation operations are embedded within the separation coefficient . Gregory (1988) developed an equation for grain separation using dimensional analysis. He derived mathematical model to simulate the threshing process in a conventional and axial flow combines. The basic equation is:

$$F_g = e^{-\left[\gamma\left(P/E_N\right)\left(L/N\right)\right]nN/F_q} \quad (2.7)$$

Where,

F_g = fraction of grain lost due to incomplete threshing

γ = ratio of straw to grain

P = power required, W

E_N = energy needed per sec of impact to detach a unit mass of grain, J/s

L = length of concave, m

n = number of bars

N = rotor speed, rpm

F_q = Gregory feed rate, kg/s

Trollope (1982) developed a mathematical model of the threshing process in a conventional combine harvester. He derived an interesting set of differential equations which relate the variables in a tangential unit. One of the equations is expressed as:

$$(g_u + g_t)cv = k_1(\omega F_r - v) \quad (2.8)$$

Where,

g_u = ratio of unthreshed grain head in cylinder concave unit

g_t = ratio of threshed grain and free chaff in the unit

c = concave clearance, m

v = velocity of material, m/s

k_1 = constant

ω = angular velocity of cylinder, rad/s

F_r = feed rate, kg/s

Other researchers have quantified the grain separation using the difference of two exponential functions, by taking into consideration the threshing/migration and separation operations. The coefficients in such functions are also influenced by crop properties, functional and design parameters of threshing units. The first of such examples was the equation developed by Alferov and Braginec (1972):

$$Ss = (1 - e^{-\lambda_1 x} - S_n \frac{1}{\lambda_1 - \lambda_0}\left(e^{-\lambda_0 x} - e^{-\lambda_1 x}\right) \quad (2.9)$$

Where

$x =$ position within the threshing length, m

S_n = mass of un-threshed grain, kg

λ_0 = coefficient of threshing units

λ_1 = coefficient of crop properties

The grain separation model developed by Huynh *et al*., (1982) used stochastic concepts to quantify the threshing process in a tangential unit. Thus, for threshing loss:

$$V_h = e^{-\lambda_t t_c} \quad (2.10)$$

Where

V_h = Huynh threshing loss, %

λ_t = mean threshing rate, t^{-1}

t_c = dwell time (time duration of grains in the threshing unit)

This forerunner model represents a good approach for threshing process description. The difficulty lies in measuring or estimating the time in which the grains remain within the

threshing space, as well as the material velocity, which is variable over the threshing length (Miu, 2002). The Threshing and separation process can be divided into the following sections (Huynh *et al*., 1982; Miu, 1994 and Miu, 1995)

a. Detachment of the grain from the ears by which the grain becomes free separable grain in the threshing space
b. Segregation of free grain kernels through the straw mat to the concave/grate surface
c. Passage of free grain kernels through the openings of concave or grates.

The probability that grains will reach the separation surface is the same over the separation length as is the probability of free grain passage through the openings of separation surface (Huynh *et al*., 1982; Mailander, 1984; Miu, 1994, 1995; Miu *et al*., 1997; Kutzbach and Quick, 1999). The probabilistic laws that respectively describe the above mentioned events have been identified as in equations 2.11 and 2.12:

a. $f(x) = \lambda e^{-\lambda x}$ (2.11)

b. $g(x) = \beta e^{-\beta x}$ (2.12)

Where λ = specific threshing/segregation rate, m^{-1}, for events a and b, respectively; $\beta =$ specific separation rate for event c, m^{-1} . Huynh *et al*., (1982) assumed similar rates expressed as waiting times. This is very important since the speed of the material (implicit time rate) varies along the length x (Wacker, 1985; Gasparetto *et al*., 1989; Miu, 2002) . The distribution frequency of Unthreshed grain percentage into the threshing space is a continuous variable. Hence, the percentage of Unthreshed grain S_n is given by integrating Equation (2.11) over the length, x:

$$S_n(x) = 1 - \int_0^x \lambda e^{-\lambda \xi d\xi} = e^{-\lambda x} \quad (2.13)$$

At the end of the threshing space (e.g., *x*=*L* for axial unit), the un-threshed grain becomes threshing loss, V_t that is:

$$V_t = S_n(L) = e^{-\lambda L} \quad (2.14)$$

Free grain kernels can separate, therefore their passage through the straw mat, and openings (random events b and c) are independent and successive. According to probability theory, the joint probability density, $S_d(x)$ of the sum of two independent and steady random variables with the densities *f*(*x*) and *g*(*x*) equals the convolution (Miu, 2002) of their individual probability densities:

$$S_d(x) = f(x) * g(x) = \int_0^L f(z)g(x-z)dz \quad (2.15)$$

Thus, we get:

$$S_d(x) = \frac{\lambda\beta}{\lambda-\beta}(e^{-\beta x} - e^{-\lambda x}) \quad (2.16)$$

The cumulative distribution function, $S_s(x)$, of separated grain is found by integrating the probability density function to get:

$$S_s(x) = \frac{1}{\lambda-\beta}\left[\lambda\left(1 - e^{-\beta x}\right) - \beta(1 - e^{-\lambda x})\right] \quad (2.17)$$

Since the material throughput is constant from the initial assumption, in the cross section of threshing space at any current position *x* of separation length, the *mass balance* can be written using the *unthreshed grain* S_n, *separated grain* S_s and *free grain percentage* S_f as follows:

$$S_n\,(x) + S_s\,(x) + S_f\,(x) = 1 \quad (2.18)$$

From Eqs. (2.13), (2.17) and (2.18) we get the percentage of free separable grain S_f as follows:

$$S_f(x) = \frac{\lambda}{\lambda-\beta}(e^{-\beta x} - e^{-\lambda x}) \quad (2.19)$$

At the end of threshing space (x=L) the free grain becomes *separation loss V*s:

$$V_s = S_f(L) = \frac{\lambda}{\lambda-\beta}(e^{-\beta L} - e^{-\lambda L}) \quad (2.20)$$

Fig. 2.2 shows the graphs of unthreshed grain S_n (x), free grain S_f (x) and cumulative separated grain S_s(x) for an axial threshing unit. It can be observed that the fraction of unthreshed grain decreases exponentially. The fraction of free grain increases to a maximum. It then decreases to a value due to grain separation.

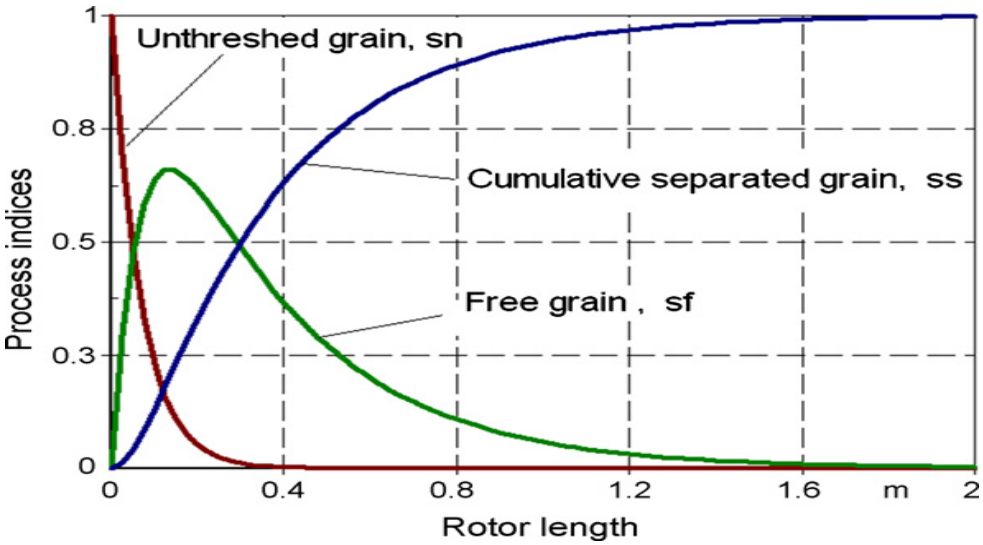

Fig. 2.2 – Example of variation of unthreshed grain, free grain and cumulative separated grain in an axial unit. (*source*: Kutzback and Quick, 1999)

Based on Eqs., (2.13), (2.17 – 2.19), we can write the continuity equation of the process quality indices over the length of threshing space as (Miu, 2001a, b):

$$\frac{1}{\beta}\frac{\partial^2 S_s}{\partial x^2} + \frac{\partial S_s}{\partial x} = \lambda S_n \qquad (2.21)$$

Separation efficiency describes the separation intensity along the length of separation space (Wacker, 1985). According to Miu *et al*., (1997), the *continuous separation efficiency effs* (*x*) at the current position *x* of separation length is defined as the ratio between separated grain mass on the differential interval d*x* and available grain mass to-be-separated to the rear of threshing unit. This can be mathematically expressed as follows:

$$eff_s = \frac{S_d}{1-(V_t-S_s)} \quad (2.22)$$

Where V_t = Threshing loss, %

The grain separation efficiency represents the probability of separation of the remaining available (separable) grain. Grain separation efficiency is a useful index for comparison of the work of similar threshing units with different sizes. Miu (1994, 1995) has developed the universal mathematical model for grain threshing and separation. It is called "universal" because the model is valid for both tangential and axial combine threshing units (with axial or tangential feeding (Miu, 2002) in different crops. The distribution frequency of un-threshed grain percentage into the threshing space is a continuous variable. At the end of the threshing space (e.g. $x = L$ for axial unit), the un-threshed grain becomes threshing loss, V_t (%), that is:

$$V_t = S_n(L) = e^{-\lambda_s L} \quad (2.23)$$

Where, S_n is the percentage of un-threshed grain, λ_s is the space increments between respective successive event changes, m^{-1}, L is the length of the threshing space, m.

2.6.2 Models for stationary grain threshers

Enaburekan (1994) developed mathematical and optimization models for the threshing process in a stationary grain thresher using wheat and sorghum. He developed, among others, the following threshing efficiency model:

$$E_t = 1 - e^{-3k_T\rho_g(1-M)VWDL/2F_rC} \quad (2.24)$$

Where E_t = the threshing efficiency, %

k_T = threshing constant

ρ_g = Crop bulk density, kgm^{-3}

M = Crop moisture content, %, dry basis

V= velocity of threshing cylinder, m/s

W= width of thresher, m

D = effective drum diameter, m

L = concave length, m

F_r = Crop mass feed rate, kg/s

C = concave clearance, m

Ndirika (1997) developed mathematical and optimization models for the threshing process in a stationary grain thresher using millet and sorghum. He developed, among other things, the following threshing model:

$$T_e = 1 - e^{\frac{-1.5k_t\rho_g DVL_C}{(1-M)F_r}} \quad (2.25)$$

Where

T_e = The threshing efficiency parameter, %

k_t = Threshing constant

ρ_g = Bulk Density, kg/m^3

V = Cylinder velocity, m/s

L_C = Concave length, m

F_r = Feed rate, kg/s

D = Cylinder diameter, m

M = moisture content, %, dry basis

Simonyan (2006) developed cleaning efficiency model for sorghum thresher:

$$\eta_c = 0.41\frac{\rho_g M}{\rho_s \theta_s} - 10.21\frac{\rho_p L V_t V_a}{\propto_s F_r} + 93.09 \quad (2.26)$$

Where

η_c = Cleaning efficiency, %

ρ_g = Grain bulk density, kgm^{-3}

M = Grain moisture content, %

ρ_s = Straw bulk density, kgm^{-3}

M_s = Straw moisture content, %

ρ_p = Particle density, kgm^{-3}

V = Threshing speed, ms^{-1}

V_a = Air velocity, ms^{-1}

$\propto_s$ = Sieve oscillating frequency, t^{-1}

F_r = Feed rate, kgh^{-1}

However, it could be observed that in Enaburekhan (1994) and Ndirika (1997) models the type of crop and the configurations of the threshers were quite different from those of the maize dehusker- sheller (for example rasp bar cylinder configuration against peg tooth arrangement). In both cases, the determination of crop constant is subject to the cultivar of the crop under consideration whereas the method of dimensional analysis used in modeling

the dehusker sheller provides objective solution of the constant of multiplication or summation. Again, in the model of Enaburekan (1994), there was the issue of clarification between the width of the thresher and the concave length. The model developed in this study considered the threshing length and considered the simpler method of analyzing the shelling process as successive event changes over the length instead of using the dwell time as done by Huynh, *et al*.,(1982), Enaburekhan (1994) and Ndirika (1997). The cleaning efficiency model for stationary sorghum thresher developed by Simonyan (2006) was completely different from the shelling models developed in this study.

Also, studies on modeling of the maize shelling process for stationery power operated machines are not widely accomplished and reported. The analysis of the research results for the other models in the literature leads the following remarks:

i. Most of the researches have had as initial aim the knowledge and understanding of the threshing and separating processes.
ii. All presented functions represent valuable approaches for modeling of threshing and separation processes.
iii. Most previous work has been done on conventional combines having rasp bar cylinders for threshing
iv. Many studies and researches have reported on variables that affect separation only
v. The models developed have used different assumptions for certain types of threshing units and crops for particular test run conditions.

2.7 Dimensional Analysis in Modeling

Dimensional analysis is a conceptual tool often applied in engineering to understand physical situations involving certain physical quantities. It is also used to form reasonable hypotheses about complex physical situations that can be tested by experiment or by more developed theories of the phenomena, and to categorize types of physical quantities and units based on their relations to or dependence on other units, or their "dimensions", or their lack thereof (Gibbings, 2011). Fourier developed Dimensional analysis based on the idea that the physical laws like should be independent of the units employed to measure the physical variables. This led to one to the conclusion that meaningful laws must be homogeneous equations in their various units of measurement, a result which was eventually formalized in the Buckingham π theorem. This theorem describes how every physically meaningful equation involving n variables can be equivalently rewritten as an equation of $n - b$ dimensionless (*pi*) parameters, where b is the number of fundamental dimensions used. Furthermore, and, most important, it provides a method for computing these dimensionless parameters from the given variables. In this study, dimensional analysis was used to develop prediction equations under consideration. It was used to obtain functional relationship between parameter and the independent variables (Ain, 2001).

2.7.1 Determination of *pi* terms

The only restriction which has been placed on the Pi terms is that they be dimensionless and independent. There are several procedures to determine suitable set of these terms. The usual method used, however may involve writing auxiliary dimensionless equations, assigning arbitrary numerical values to get the unknown exponents, solving the resulting

set of simultaneous equations, combining the results to form one Pi term; repeating the initial steps until all Pi terms have been determined. The results would then be combined to form an equation of the form:

$$\pi_1 = F\ (\pi_2,\ \pi_3,\ \pi_4 \ldots \ldots \pi_s) \qquad (2.\ 27)$$

Where $s = n - b$, n and b as defined above.

The generated component equations were combined either by summation or product function to give the prediction equations. However, Murphy (1950) stated that it is expedient to investigate the conditions which are necessary or sufficient for certain simple combination to exist. Shafii *et al*., (1996) stated that in order to verify that an equation is correct, at least $2m-3$ tests need to be conducted, where m is the number of the pi terms.

2.7.2 Product function of component equation

Murphy, (1950) has outlined the procedures as explained in the following paragraphs. If three pi terms are involved, the component equations may be combined to form the general prediction equation by multiplication as:

$$\pi_1 = k\ (\pi_1)_{\overline{3}}\ (\pi_1)_{\overline{2}} \qquad (2.28)$$

Where

k is a constant.

$(\pi_1)_{\overline{3}}$ is the relationship of π_1 against π_2, holding π_3 constant

$(\pi_1)_{\overline{2}}$ is the relationship of π_1 against π_3, holding π_2 constant

Thus,

$$\pi_1 = F(\pi_2)(\pi_3) \qquad (2.29)$$

Experiments would be carried out varying π_2 and holding π_3 constant. The following relation could be established

$$(\pi_1)_{\overline{3}} = f_1(\pi_2, \bar{\pi}_3) \quad (2.30)$$

From another experiment, π_3 as variable and π_2 as constant

$$(\pi_1)_{\overline{2}} = f_2(\bar{\pi}_2, \pi_3) \quad (2.31)$$

To determine the constant k in equation 2.28, let assume that the component equations are simply multiplied to form the general equation as:

$$F(\pi_2, \pi_3) = f_1(\pi_2, \bar{\pi}_3) f_2(\bar{\pi}_2, \pi_3) \quad (2.32)$$

If this assumption is true, the first set of Pi terms with π_3 constant, gives

$$F(\pi_2, \bar{\pi}_3) = f_1(\pi_2, \bar{\pi}_3) f_2(\bar{\pi}_2, \bar{\pi}_3) \quad (2.33)$$

From which

$$f_1(\pi_2, \bar{\pi}_3) = \frac{F(\pi_2, \bar{\pi}_3)}{f_2(\bar{\pi}_2, \bar{\pi}_3)} \quad (2.34)$$

The second set of Pi terms, with π_2 constant, from equation (2.32) gives,

$$F(\bar{\pi}_2, \pi_3) = f_1(\bar{\pi}_2, \bar{\pi}_3) f_2(\bar{\pi}_2, \pi_3) \quad (2.35)$$

From which

$$f_2(\bar{\pi}_2, \pi_3) = \frac{F(\bar{\pi}_2, \pi_3)}{f_1(\bar{\pi}_2, \bar{\pi}_3)} \quad (2.36)$$

Putting the values of $f_1(\pi_2, \bar{\pi}_3)$ and $f_2(\bar{\pi}_2, \pi_3)$ from equations 2.34 and 2.36 respectively into equation 2.32 would give;

$$F(\pi_2, \pi_3) = \frac{F(\pi_2, \bar{\pi}_3) F(\bar{\pi}_2, \pi_3)}{f_2(\bar{\pi}_2, \bar{\pi}_3) f_1(\bar{\pi}_2, \bar{\pi}_3)} \quad (2.37)$$

However, both π_2 and π_3 are constant in the denominator of equation (2.37)

Thus,

$$F(\bar{\pi}_2, \bar{\pi}_3) = f_1(\bar{\pi}_2, \bar{\pi}_3) f_2(\bar{\pi}_2, \bar{\pi}_3) \quad (2.38)$$

Hence,

$$F(\bar{\pi}_2, \pi_3) = \frac{F(\pi_2,\bar{\pi}_3)F(\bar{\pi}_2,\pi_3)}{F(\bar{\pi}_2,\bar{\pi}_3)} \quad (2.39)$$

From equation 2.37, constant k in equation 2.27could be deduced as:

$$k = \frac{1}{F(\bar{\pi}_2,\bar{\pi}_3)} \quad (2.40)$$

Also, equation 2.40 shows the form of the general equation and indicates that the two component equations must have the same form. However, this is not a sufficient condition for the combination of component equation to be a product. A validity test must be performed. A test for the validity of combining the component equations as a product may now be developed by assuming that a third component equation is determined from a third set of data in which one of the Pi terms is held constant at a different value than in preceding set of data (Murphy, 1950). To test the validity of the component equation be a product, the right hand sides of the two general component equations must be equal. The component equations were determined by holding the π_2 constant at a value of $\bar{\pi}_2$, but if valid, it could also have been determined from a set of data in which $\pi_2 = \bar{\pi}_2$.

Then,

$$F(\bar{\pi}_2, \pi_3) = \frac{F(\pi_2,\bar{\pi}_3)F(\bar{\pi}_2,\pi_3)}{F(\bar{\pi}_2,\bar{\pi}_3)} \quad (2.41)$$

The right –hand side of equation 2.40 must equal the right-hand side of equation 2.41.

Hence.

$$\frac{F(\bar{\pi}_2,\pi_3)}{F(\bar{\pi}_2,\bar{\pi}_3)} = \frac{F(\bar{\pi}_2,\pi_3)}{F(\bar{\pi}_2,\bar{\pi}_3)} \quad (2.42)$$

Also, if π_3 had been held constant at different value, $\bar{\pi}_3$

$$\frac{F\,(\pi_2,\overline{\pi}_3)}{F(\,\overline{\pi}_2,\overline{\pi}_3)} = \frac{F\,(\pi_2,\overline{\pi}_3)}{F(\,\overline{\pi}_2,\overline{\pi}_3)} \tag{2.43}$$

Equation 2.42 and 2.43 constitute a test for the validity of equation 2. 39. That is, if the supplementary sets of date satisfy either equation 2.42 or 2.43, the general equation may be formed by multiplying the component equations together and dividing by the constant as indicated in 2.40. Data from physical plots would more often plot to form a curved surface in space but would frequently form a plane in logarithmic space. If a plane surface is formed in a logarithmic space, the component equations are of the form

$$(\pi_1)_{\overline{2}} = a\,{\pi_3}^m \tag{2.44}$$

$$(\pi_1)_{\overline{3}} = b\ {\pi_2}^n \tag{2.45}$$

Where a, b and c are absolute values that characterize the space, m and n are values of the power to which pi is raised.

The intersection of the plane surface with plane parallel to the same coordinate plane will be straight parallel lines., thus

$$(\pi_1)_{\overline{2}} = c\ {\pi_3}^m \tag{2.46}$$

If the equations of the lines for two different values of π_2 (Eqs 2.44 and 2.45) are tested for combination by multiplication by substituting in Eq 2.42, it results in

$$\frac{a\,{\pi_3}^m}{a{\overline{\pi}_3}^m} = \frac{c\,{\pi_3}^m}{c\,{\overline{\pi}_3}^m} \tag{2.47}$$

Since this is an equality for all values of a and c the component equations maybe combined as a product giving,

$$\pi_1 = \frac{a\,{\pi_3}^m b\ {\pi_2}^n}{a{\overline{\pi}_3}^m} \tag{2.48}$$

$$= \frac{b\ {\pi_2}^n\ {\pi_3}^m}{{\overline{\pi}_3}^m} \tag{2.49}$$

If the data forms a plane in ordinary space, the component equations will be of the form

$(\pi_1)_{\overline{2}}$ = a + b π_3 (2.50)

$(\pi_1)_{\overline{3}}$ = e + d π_2 (2.51)

and a supplementary component equation would be in the form of :

$(\pi_1)_{\overline{2}}$ = e +b π_3 (2.52)

If the test for combination by multiplication, equation 2.42, is applied to equations 2.50 and 2.52 the results become:

$$\frac{a+b\ \pi_3}{a+b\ \overline{\pi}_3} = \frac{e+b\ \pi_3}{e+b\ \overline{\pi}_3} \tag{2.53}$$

Or, ab $\overline{\pi}_3$ + ebπ_3= eb$\overline{\pi}_3$ + ab π_3 (2.54)

Which is valid only when a = e, that is, when π_1 is independent of π_2 . Hence this fails the test for combination as a product except in a special case in which π_1 is independent of one of the variables.

2.7.3 Summation function of component equation

Also Murphy, (1950) stated that if it is assumed that:

F (π_2, π_3) = f(π_2) + g (π_3) (2.55)

Then,

$F(\overline{\pi}_2, \pi_3) = f(\overline{\pi}_2) + g(\pi_3)$ (2.56)

From which;

$g(\pi_3) = F(\overline{\pi}_2, \pi_3) - f(\overline{\pi}_{2,})$ (2.57)

Similarly,

$f(\pi_2) = F(\pi_2, \bar{\pi}_3) - g(\bar{\pi}_3)$ (2.58)

Equation 2.55 may therefore be written as:

$$F(\pi_2, \pi_3) = F(\pi_2, \bar{\pi}_3) - g(\bar{\pi}_3) + F(\bar{\pi}_2, \pi_3) - f(\bar{\pi}_2) \quad (2.59)$$

$$= F(\pi_2, \bar{\pi}_3) + F(\bar{\pi}_2, \pi_3) - F(\bar{\pi}_2, \bar{\pi}_3) \quad (2.60)$$

Equation 2.60 shows that if the components equations are to be combined by addition to form the general prediction equation, a constant must be subtracted from the sum of the component equations. With the form of the resultant equation established, a test for the validity of combination by addition may be developed by considering a supplementary set of data in which one of the pi terms is held constant at a value different from its magnitude in the original component equation. If π_2 is held constant at a new value $\bar{\pi}_2$, Eq 2.60 becomes

$$F(\pi_2, \pi_3) = F(\pi_2, \bar{\pi}_3) + F(\bar{\pi}_2, \pi_3) - F(\bar{\pi}_2, \bar{\pi}_3) \quad (2.61)$$

The right hands of eqs 2.60 and 2.61 are equal, hence

$$F(\bar{\pi}_2, \pi_3) - F(\bar{\pi}_2, \bar{\pi}_3) = F(\bar{\pi}_2, \pi_3) - F(\bar{\pi}_2, \bar{\pi}_3) \quad (2.62)$$

A similar test may be used if the supplementary test is run holding π_3 constant at a new value. Thus,

$$F(\pi_2, \bar{\pi}_3) - F(\bar{\pi}_2, \bar{\pi}_3) = F(\pi_2, \bar{\pi}_3) - F(\bar{\pi}_2, \bar{\pi}_3) \quad (2.63)$$

If the data plot to form plane surface in space, the component equation and the supplementary equation will have the form given in equations (2.50) and (2.51). The first and the third may be substituted in equation (2.61), giving

$$a + b\pi_3 - (a + b\bar{\pi}_3) = e + b\pi_3 - (e + b\bar{\pi}_3) \quad (2.64)$$

This is valid for all values of π_3, hence the component equations may be found by addition, as indicated in (2.61), giving:

$$\pi_1 = c + d\pi_2 + a + b\pi_3 - (a + b\bar{\pi}_3) \quad (2.65)$$

$$= (c - b\bar{\pi}_3) + d\pi_2 + b\pi_3 \quad (2.65a)$$

If the test for formation of the general equation by addition of the component equations is applied to data which plots as a straight line in logarithmic space, equation (2.47) gives:

$$a\pi_3^m - a\bar{\pi}_3^m = c\pi_3^m - c\bar{\pi}_3^m \quad (2.66)$$

Equation 2.66 shows that the test satisfies only when a = c, hence they cannot be combined by addition. They can only be combined by multiplication as earlier pointed.

2.8 Model Performance Evaluation

Wilmot (1982) suggested that bias and root mean square error (RMSE) are among the "best" overall measures of model performance.

$$\text{Bias} = \frac{1}{N}\sum_{i=1}^{N}(P_i - M_i) \quad (2.67)$$

Where P and M are predicted and observed values of the variable of interest, respectively, and N is the number of observations.

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(P_i - M_i)^2} \quad (2.68)$$

Mean Square deviation (MSD) and square bias (SB) and lack of correlation weighted by the standard deviation (LCS), is calculated using Kobayashi and Salam (2000) equations as:

$$\text{MSD} = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2 \quad (2.69)$$

$$SB = (\overline{P} - \overline{O})^2 \quad (2.70)$$

$$LCS = 2 \times SD_P \times SD_O \times (1 - r) \quad (2.71)$$

Where

$\overline{P}$ and $\overline{O}$ = average predicted by the model and measured values. SD_P and SD_O = standard deviations of predicted and observed values, respectively; r = the correlation coefficient between predicted and observed values. Model performance was quantified by calculating the standard error (SE) and average absolute deviation (AAD) as Yusuf, 2001):

$$SE = \frac{\sqrt{\Sigma(y_m - y_p)^2}}{n} \quad (2.72)$$

$$AAD = \frac{\sum |y_m - y_p|}{n} \quad (2.73)$$

Where ym and yp represent measured and predicted values, respectively and n is the number of observations. Coefficient of efficiency (Legates and McCabe, 1999, Krause *et al*., 2005) is given as:

$$E = 1 - \frac{\sum_{i=1}^{n} |O_i - P_i|}{\sum_{i=1}^{n} |O_i - \overline{O}|} \quad (2.74)$$

Where

O_i = Observed data

Pi = Model simulated data.

$\overline{O}$ = mean observed data

The statistic E examines whether the difference between the model simulations and the measured data is as large as the variability with the observed data. The range of E lies

between 1.0 (perfect fit) and – ∞. An efficiency of lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model. The largest disadvantage of E is the fact that the difference between the observed and the predicted values are calculated as squared values. As s result, larger values in a time series are strongly overestimated whereas lower values are neglected (Legates and McCabe, 1999). The index of agreement, *d* , was proposed by Wilmot (1981) to overcome the insensitivity of E and r^2 to differences in the observed and predicted means and variances (Legates and McCabe, 1999). The index of agreement represents the ratio of the mean square error and the potential error (Wlmot, 1984) and is defined as:

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \overline{O}| + |O_i - \overline{O}|)^2} \quad (2.75)$$

Range of *d* is similar to that of r^2 and lies between 0 (no correlation) and 1 (perfect fit).

2.8.1 Model verification

Yusuf (2001) stated that for the purpose of utilization of the developed model for either determination of production possibilities, design, improving decision making process or simple representation of a complex agricultural system, the model should be verified. It concerns with establishing the rectitude of the logical structure of the model. In The slope and coefficient of determination (r^2) values were used as indices of agreement between plotted observed and predicted values. Model verification involves comparing the observed values with predicted results. The slope and coefficient of the determination (r^2) value are then used as indices of agreement with observed data. To test the significance of b (slope), the residual mean square was computed as Gomez and Gomez (1984):

$$S^2{}_{y.x} = \frac{\sum y^2 - \frac{(\sum xy)^2}{\sum x^2}}{n-2} \quad (2.76)$$

Where

$S^2{}_{y.x}$= the residual mean square

y^2= square of deviates of y

x^2= square of deviates of x

xy = product of x and y deviates

n-2 = the degrees of freedom

The t value , $t_b$is computed as:

$$t_b = \frac{b}{\sqrt{\frac{S^2{}_{y.x}}{\sum x^2}}} \quad (2.77)$$

To test the hypothesis on the intercept, the t value is computed as:

$$t_\alpha = \frac{\alpha - \alpha_0}{\sqrt{S^2{}_{y.x}\left(\frac{1}{n} + \frac{\bar{x}^2}{\sum x^2}\right)}} \quad (2.78)$$

Where

b = estimate of slope regression parameter

α = intercept of the line on the Y axis

α_0 = specified value of the intercept depending on the research problem

2.8.2 Model validation

This is the establishment of verisimilitude of the responses from the verified model and comparable observation. Main methods used for validation are (Gass, 1983): Regression and correlation analysis; goodness of fit (F-test); comparison of mean values (t-test); analysis of variance and covariance; analysis of residuals; χ^2 test of the best approach to normality; stepwise regression and sensitivity analysis.

2.8.3. Sensitivity analysis

Sensitivity analysis is used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model. Parameter sensitivity is usually performed as a series of tests in which the modeler sets different parameter values to see how a change in the parameter causes a change in the dynamic behavior of the stocks. By showing how the model behavior responds to changes in parameter values, sensitivity analysis is a useful tool in model building as well as in model evaluation. Sensitivity analysis helps to build confidence in the model by studying the uncertainties that are often associated with parameters in models (Breierova and Choudhari, 2001). The sensitivity methods include the utilization of the following one-at-a-time sensitivity measures: partial derivatives (PD), one standard deviation increase and decrease of inputs (±SD), a 20% increase and decrease of inputs (±20%), and a sensitivity index (SI). When an explicit algebraic equation describes the modeled relationship, the sensitivity coefficient (dimensionless) for a particular independent variable is calculated from the partial derivative of the dependent variable with respect to the independent variable (Hamby, 1994). Dimensionless sensitivity coefficients for each of the independent variables were given by Gong *et al.* (2006):

$$S_{u_1} = \frac{\partial N}{\partial u_1} . \frac{u_1}{N} \quad (2.79)$$

Where

S_{u_1} = sensitivity coefficient of variable

N = reference output (dependent variable)

u_1 = mean value of the independent variable

Ampas (2010), proposed the use of standard deviation, σ_{u_1}, instead of the mean values and presented sensitivity coefficient as:

$$S_{u_1} = \frac{\partial N}{\partial u_1} . \frac{\sigma_{u_1}}{N} \quad (2.80)$$

Saxton (1975) gave the following equation for the total value of the coefficients, $N\xi$:

$$. N\xi = \left(\frac{\partial N}{\partial u_1}\frac{u_1}{N}\right) u_1\xi + \left(\frac{\partial N}{\partial u_2}\frac{u_2}{N}\right) u_2\xi + \cdots \ldots \ldots \ldots \quad (2.81)$$

He stated that the terms in the bracket (equation 2.81) become dimensionless coefficients which express the percentage of the relative variable change transmitted to the relative dependent variable. The sensitivity coefficient shows the relative importance of each of the variable to the model solution.

2.9 Optimization

Optimization procedures refer to the study of problems in which one seeks to minimize (or maximize) a real function by choosing the values of real or integer variables from within an allowed set. (Lucor *et al.,* 2007). There is the classical approach using calculus derivatives. The interest in application of modern optimization technique is considerable, primarily as a result of development of modern computers and software (Enaburekan,

1994). Only very simple and single variable optimization problem can be solved by the classical method of derivative approach without rather extensive numerical methods. Use of genetic algorithms coupled with fuzzy logic software find greater and potential applications in the contemporary computer age.

2.9.1. Use of genetic optimization toolbox in MATLAB

Modern optimization concepts use Neural Network, Fuzzy logic and biologically- inspired algorithms such as the Genetic Algorithm (GA), Ant colony, Particle swarm, Fire fly and Bee Optimization packages (Baguda, 2014). GA's are global and robust over a broad spectrum of problems (Davis, 1991; Michalebicz, 1996). MATLAB software offers vast applications in this direction. An optimization problem with more than one objective function would require a weighting vector. This is simply weighting of the entire performance vector together to form a single aggregate performance response of the form (William and James, 1980):

$$U\lfloor y(x), w\rfloor = \sum_{i=1}^{m} w_1\, y_1(x) \qquad (2.82)$$

Where:

U= utility factor relating all the performance vector

$y(x)$ = performance response of the machine

w_i = weighting vector

Use of genetic algorithms coupled with fuzzy logic software find greater and potential applications in the contemporary computer age. Miu (2001a) carried out an optimization of design and functional parameters of threshing units based on formulation of a multi-objective genetic algorithm in relationship with Fuzzy logic using MATLAB. Design and operation parameters in connection with physical properties of certain crop are expressed

as variables of a complex constrained, non linear multi-objective problem. Solving the problem requires finding the setting of above mentioned decision variables so that an evaluation function based on process quality criteria is maximized. To solve the problem at hand a genetic algorithm is implemented. Improvements of the algorithm performance are obtained using elitist selection strategy and selective weights in the evaluation function. Once this successful evolutionary computation approach has been developed it can be incrementally adapted for other threshing units in various crops (Miu, 2001b). An optimization problem with more than one objective function such as the case in this study would require a weighting vector.

CHAPTER THREE

3.0 MATERIALS AND METHOD

3.1 Materials/Instrumentation

The materials used for this study include the following:

The existing IAR maize dehusker sheller; Mechanical Tachometre (TZ 5000 model) for speed measurements; Digital Mettler Balance (PN 1210 Model); Oven (Model 2000, Shermond, Nottingham, England); Digital stop watch and maize (QPM, ACR and TZPB) varieties.

3.2 Determination of Some Physical Properties of Selected Varieties of Maize

3.2.1 Dimensions

The linear dimensions length, width and thickness for each of the three maize varieties were determined using a vernier calipher (Fischer Scientific) having a least resolution count of 0.01 cm. Average values of 50 shelled grains were randomly selected from the experimental sample (FAO, 1994).

3.2.2 A thousand kernel mass, M_{1000}

One thousand whole kernels of each of the selected maize varieties were weighed using Mettler PN 1210 digital weighing balance with 0.01 g sensitivity.

3.2.3 Moisture content

The moisture content of whole grain and material other than grain was determined by Protimeter Grainmaster Model GRN 3000 moisture meter after calibration using the oven-dry method as stipulated by ASAE standard S358.2 (1983).

3.2.4 Bulk density

The bulk density of the maize was determined by weighing the grains packed in a container of known volume according to the procedure outlined by Waziri and Mittal (1983).

3.3 Performance Indices

The indices used and their respective equations were as determined by Ndirika (1997).

They are as follows:

$$C_p = \frac{Q_T}{t} \quad (3.1)$$

Where

C_p= capacity (Output), kg/h

Q_T= weight of whole grain collected in unit time, kg

t = Threshing time, hours.

$$\eta_T = 100 - \left(\frac{Q_u}{T_G}\right) \times 100\ \% \quad (3.2)$$

Where

η_T = Threshing efficiency, %

Q_u = Weight of Unthreshed grain in unit time, kg

T_G = Total grain input in unit time by weight, kg

$$\eta_C = \left(\frac{Q_{co}}{Q_{wo}}\right) \times 100\ \% \quad (3.3)$$

Where

η_C = Cleaning efficiency, %

Q_{co} = Weight of whole clean grain in unit time at grain outlet, kg

Q_{wo} = Weight of whole material collected in unit time at the grain outlet, kg

$$L_S = \left(\frac{Q_{sg}}{T_G}\right) \times 100\ \% \quad (3.4)$$

Where

L_S = Scatter loss, %

Q_{sg} = Weight of scattered grain collected in unit time, kg

T_G = Total grain input per unit time by weight, kg

According to Behera *et al.* (1995), the damaged grain is given by the following:

$$D_g = \left(\frac{Q_{vd}}{100}\right) \times 100\ \% \quad (3.5)$$

Where

Dg = Damaged grain, %

Q_{vd} = Weight of visually damaged grain isolated in 100 grams of threshed sample, g

3.4 Experimental Layout and Design

Performance evaluation tests were carried out separately. First, it was done to generate data for the development of the models and secondly to generate it to validate the developed models. The data generated were used for the analysis of the effects of different variables and their interactions on the performance parameters. Each experiment was a factorial design involving four crop and machine variables, speed, S, feed rate, F, concave clearance, C and Moisture content, M, each at three levels. During performance tests, values of 750, 850 and 950 rpm; 30, 40 and 50 kg/min; 35, 40 and 45 mm and 9, 12 and 15 % were used as speed, feed rate, concave clearance and moisture content (wet basis), respectively. The layout was in a completely randomized block design (3x3x3x3=81 treatments) and replicated three times in each of the model development and validation experiments. The layout and randomization for each and the analysis of variance are shown in appendix I.

3.5 Data Analysis

The analyses of the data were carried out using the SAS statistical package. The GLM procedure was used in the Analysis of variance. Duncan's multiple range tests were used to compare the differences between means for variables.

3.6 Theoretical Development of Prediction Equations

3.6.1 Description of the dehusking-shelling process

The cobs (husked) are fed in at the concave entrance forming a crop stream or mat between the concave and the cylinder. Dehusking and shelling are achieved by a combination of impact and rubbing (friction) action occurring when fast moving pegs strike the cob and force it to flow over the concave. Separation is the penetration of threshed grain through the combined husks-cob material and their passage through the concave openings (Plate III). This is achieved by the action of gravity and centrifugal force (Huynh *et al*., 1982). A.

Plate III: Cylinder Concave Configuration of the Sheller

grain fails to pass through the concave openings if only during space increments between respective successive event changes, it is not completely detached from the cob or it fails to penetrate the husk-cob mat or it cannot find an opening.Thus, it is thrown out through the cob thrower outlet. According to the concept of the universal model developed by Miu (1995) as validated by Miu and Kutzbach (2008), The threshing and separating process described above can be divided into the following three sections:

a. Detachment of the grain from the cobs by which the grain becomes *free* separable grain in the threshing space.
b. Segregation of free grain kernels through the cob mat to the concave surface
c. Passage of free grain kernels through the openings of concave.

The probability that grains will reach the separating surface is the same over the separation length as is the probability of free grain passage through the openings of separation surface (Huynh *et al*., 1982; Mailander, 1984; Miu, 1994, 1995; Miu *et al*., 1997; Kutzback and Quick, 1999).

3.6.2 Modeling assumptions

For modeling of grain threshing and separating processes, the following general assumptions have been taken into consideration (Enaburekan, 1994; Miu, 1995, Ndirika, 1997; Miu *et al*., 1998a, Miu *et al*., 1998b ; Miu and Kutzback, 2000; Miu and Kutzback, 2008).

a. The material throughput is constant; material moves through the threshing space as a continuous stratum.
b. The material to be processed is homogenous, i.e., the husks-cob are uniformly distributed within the cob mat
c. The material is homogenous in any cross section of the threshing space
d. The mass of material is continuously distributed in the threshing space and its volumetric density is a continuous function of position and time
e. Material velocity is a continuous function of the position over the length of the threshing space
f. The radial reactive forces due to grain separation do not influence the material movement.

3.6.3. Shelling efficiency

The Universal mathematical model of grain threshing and separation as developed by Miu, (1995) and validated by (Miu and Kutzback, 2008) was considered fit for describing and predicting the process performance and various variables influencing the shelling process:

i. $S_n(x) = e^{-\lambda x}$ (3.6)

ii. $S_f(x) = \frac{\lambda}{\lambda-\beta}\left(e^{-\beta x} - e^{-\lambda x}\right)$ (3.7)

iii $S_s(x) = \frac{1}{\lambda-\beta}\left[\lambda\left(1-e^{-\beta x}\right)-\beta\left(1-e^{-\lambda x}\right)\right]$ (3.8)

Where

$S_n(x)$ = Unthreshed fraction over the threshing length, x

$S_f(x)$ = Free grain, fraction

$S_s(x)$ = Cumulative separated grain, fraction

λ and β are probability density functions, in decimals, as defined on the threshing space length, x. They represent space increments between respective successive event changes. This approach was preferred to that of Huyinh *et al*. (1982) which assumed similar rates expressed as waiting times. In this study, the threshing space length becomes very crucial due to the provision of the cob thrower outlet. The variables of importance assumed to influence λ_S were: Cylinder velocity, V (m/s), maize crop feed rate, F_r, (kg/s), maize bulk density, ρ_g (kg/m^3), concave clearance, C (m) , diameter of cylinder, D and maize grain moisture content, M (%, wet basis). Thus:

$\lambda_S = f(V,\ F_r,\ \rho_g,\ C,\ D,\ M)$ (3.9)

Or $f(\lambda_S, V,\ F_r,\ \rho_g,\ C,\ D,\ M) = 0$ (3.10)

Table 3.1 shows the variables and their corresponding dimensions. According to Buckingham pi theorem, number of dimensionless groups to be formed is (6-3) =3. Note that moisture content is already in percentage (dimensionless). Thus, the following dimensional equations were expressed:

$f(\lambda, V,\ F,\ \rho,\ \ C,\ D\ ) = 0$ (3.11)

$[L^{-1}]^{c1}[LT^{-1}]^{c2}[MT^{-1}]^{c3}[ML^{-3}]^{c4}[L]^{c5}[L]^{c6} = 0$ (3.12)

From which the auxiliary equations may be written by using the indices as

M: $c_3 + c_4 = 0$ (3.13)

L: $- c_1 + c_2 - 3c_4 + c_5 + c_6 = 0$ (3.14)

T: $- c_2 - c_3 = 0$ (3.15)

Table 3.1: Variables and their Corresponding Dimensions

Variable	Symbol	Unit	Dimension $[M][L][T]$
Shelling rate	λ_S	m^{-1}	L^{-1}
Cylinder velocity	V	ms^{-1}	LT^{-1}
Feed rate	F_r	kgs^{-1}	MT^{-1}
Concave clearance	C	m	L
Diameter of cylinder	D	m	L
Bulk density	ρ_g	$kgms^{-3}$	ML^{-3}

Thus the matrix below is formed

	c_1	c_2	c_3	c_4	c_5	c_6
M:	0	0	1	1	0	0
L:	-1	1	0	-3	1	1
T:	0	-1	-1	0	0	0

For solution of the indices the value of the determinant of the *3 x 3* matrix formed must not be zero. To achieve this, the following indices were selected

	c_2	c_4	c_5
M	0	1	0
L	1	-3	1
T	-1	0	0

The determinant of this matrix is not zero.

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & -3 & 1 \\ -1 & 0 & 0 \end{bmatrix} = 1$$

With 6 unknowns and 3 equations, 3 arbitrary values for $c_1, c_3 \; and \; c_6$ were assigned to solve the equations. Thus:

(i) With $c_1, c_3 \; and \; c_6$ as 1, 0, and 0 respectively, and substituting into equations (3.7-3.9), c_2 = 0, c_4 = 0 , and c_5 = 1

Hence $\pi_1 = \lambda_S C \; [L^{-1}L]$ (3.16)

(ii) With $c_1, c_3 \; and \; c_6$ as 0, 1 , 0 respectively and substituting into equations (3.13-3.15, c_2 = -1, c_4 = -1 , and c_5 = -2

Hence $\pi_2 = \frac{F_r}{P_g V C^2}$ $\frac{MT^{-1}}{[ML^{-3}][LT^{-1}][L^2]}$ (3.17)

(iii)With $c_1, c_3 \; and \; c_6$ as 0, 0 , 1 respectively and substituting into equations (3.13-3.15), c_2 = 0, c_4 = 0 , and c_5 = -1

(iv)Hence $\pi_3{}' = \frac{D}{C}$ $\frac{[L]}{[L]}$ (3.18)

M is already dimensionless, hence it was incorporated in equation 3.18. Thus

$$\pi_3 = \frac{DM}{C} \tag{3.19}$$

Plots of π_1 against π_2 holding π_3 constant, $(\pi_1)_{\overline{3}}$; and π_1 against π_3 holding π_2 constant $(\pi_1)_{\overline{2}}$, were made in order to come up with component equations..The component equations relating the different variable during the model development stage using dimensional analysis were generated through the use of values obtained from the dimensionless plots.

3. 6. 4 Grain damage dimensionless groups

The damage incremental rate, $\lambda_{D,}$ of the grain within the threshing space length would be predicted. As in shelling, the variables of importance assumed to influence λ_D were: Cylinder velocity, V (m/s), maize crop feed rate, F_r (kg/s), maize bulk density, ρ_g (kg/m^3), concave clearance, C (m) , diameter of cylinder, D and maize grain moisture content, M (%, wet basis). Thus:

$\lambda_D = f(V,\ F_r,\ \rho_g,\ \ C,\ D\ \ M)$ (3.20)

Or $f(\lambda_D, V,\ F_r,\ \rho_g,\ \ C,\ D\ \ M) = 0$ (3.21)

Using the same procedure as for shelling, the dimensionless pi terms were determined thus: $\pi_1 = \lambda_D C$, $\pi_2 = \frac{F_r}{V\rho_g C^2}$, and $\pi_3 = \frac{DM}{C}$

3.6.5. Grain loss dimensionless groups

Unthreshed grain could not pass through the concave hole openings. So it would pass through the cob thrower outlet as scatter losses. Threshed free grain in the crop stream mat that could not pass through the concave opening at the end of the threshing length would also be thrown out through this outlet. This separation loss was considered. The variables of importance assumed to influence the separation parameter, β were: Cylinder velocity, V (m/s), maize crop feed rate, F_r (kg/s), maize bulk density, ρ_g (kg/m^3), concave clearance, C (m) , diameter of cylinder, D and maize grain moisture content, M (%, wet basis). Thus:

$\beta = f(V,\ F_r,\ \rho_g,\ C,\ D\ \ M)$ (3.22)

Or $f(\beta, V,\ F_r,\ \rho_g,\ C,\ D\ \ M) = 0$ (3.23)

Using the same procedure as above, the dimensionless pi terms were determined thus:

$\pi_1 = \beta C$, $\pi_2 = \frac{F_r}{\rho_g V C^2}$, and $\pi_3 = \frac{DM}{C}$

3.7 Model Performance Evaluation

In this study, qualitative performance was assessed using the slope and intercept of linear regression between predicted and observed values.. The value of the coefficient of determination (r^2) described the total variance explained by the models. Root mean square

error (RMSE), bias, and efficiency as explained in section 2.8 were used. In Model Verification a plot of observed values against predicted values was made to fit a straight line through the data. Coefficient of determination (r^2) value, significance of slope and intercept, according to Gomez and Gomez (1984) as explained in section 2.8.1 were used as indices of agreement with observed data. In this study, differential sensitivity analysis was used also as a validation tool to establish the relative importance of each variable to the model solution. The sensitivity analysis procedure as described by Saxton, (1975) and Gong *et al*. (2006) and explained in section 2.8.3. was used.

3.8 Optimization

Optimization based on formulation of a multi-objective genetic algorithm (Miu, 2001b; Miu and Perhinschi, 2001) was used in this study. MATLAB R2008a Genetic optimization toolbox was used to yield the values of variables for optimum performance of three indices. The shelling efficiency was maximized while grain damage and grain loss were minimized. The functional parameters, i.e variables (x) and performance criteria objectives (y) considered in the decision process in search of optimal solution of this study are:

$$x = [\rho_g, F_r, d, v, c, m, l] \quad (3.25)$$

and

$$y = [SE, GD, GL] \quad (3.26)$$

Where:

ρ_g = Grain bulk density, kg/m^3

F_r = Feed rate, kg/h

d = Drum diameter, m

v = Cylinder speed, m/s

c = Concave clearance, m

m = Moisture content, % wet basis

l = shelling length, m

SE = Shelling efficiency, y_1 %

GD = Grain damage,y_2, %

GL = Grain loss, y_3, %,

Based equation 2.82 the evaluation function in this study has the expression;

$$EF = -w_1 y_1 + w_1 y_2 + w_1 y_3 \quad (3.27)$$

$y_1, y_2\ and\ y_3$ Represent the shelling efficiency, grain damage and grain loss, respectively. MATLAB is based on minimization, therefore, for maximization (shelling efficiency), the sign changes. For minimization (grain damage and grain loss), the convention stands as it is. The three objectives performance response is assumed to be equally important therefore each weighting vector w has component equal to 1/3. In order to avoid the problem of convergence to a local optimal of the algorithm because of equal weight vector, a selective weights' vector was also considered with 3/9, 2/9 and 4/9 representing $w_1, w_2\ and\ w_3$ respectively. The variables to be optimized were found within the upper and lower bound limits. The values obtained for bulk density during the determination of physical properties of maize were used to define the bounds. other bounds were set based on evaluation experiments. The population type, creation function, scaling function, selection function, mutation function and cross over functions, which are features of the

genetic algorithm optimization, used were double vector, feasible population, rank, roulette, adaptive feasible and heuristic respectively. Default cross over rate of 1.2 was used. All these were incorporated in the toolbox and the program was run for both equal weights and selective weights.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Some Physical Properties of Selected Varieties of Maize (*Zea mays L*).

The summary of the mean values and standard deviations for the linear dimensions (length, width and thickness), one thousand grain mass, bulk density and the computed geometric mean diameters at different moisture contents for the maize varieties is presented in table 4.1.The statistical package (SAS) output is shown in table AII-1 of Appendix II. The summary of the Analysis of variance for all the parameters is presented in table 4.2. Duncan multiple range grouping is presented in table 4.3. Mean values of length, width thickness, thousand grain mass and bulk density obtained for TZPB variety are similar to those reported by Soliman and Abdulmaqsud (2007). The effects of moisture content and maize grain variety were highly significant for all the parameters considered. For ACR variety, as the moisture was decreased from 15 to 9 %, mean values of the properties, length, width, thickness, thousand grain mass and geometric mean diameter decreased as follows: 1.184 - 1.035 cm, 1.027 - 0.828 cm, 0.450 - 0.374 cm, 291.79 - 246.81 g and 0.818-0.684 cm, respectively (table 4.1). The reason for the decrease in mean values of these properties could be due to shrinkage of the material as the moisture decreases. This

agrees with some research findings: (Mohammed, 2002, Karababa, 2006; Ndirika and Oyeleke, 2006; Sobukola *et al.,* 2008; Seifi and Alimardani, 2010). The mean value for Bulk density, however, increased from 801.93 to 876.40, kgm^{-3} as the moisture decreased (15-9 %). The increase in bulk density could be due to decrease in volume relative to mass at lower moisture. This trend agrees with (Mohsenin, 1986, Karababa and Coskuner, 2007; Sobukola *et al.,* 2008).

Table 4.1: Summary of the Mean Values for the Dimensions and other Selected Properties of the Maize Varieties at Different Moisture Contents

DIMENSIONS	MC, % (dry basis)	Maize varieties ACR	TZPB	QPM
LENGTH (CM)	**9**	1.035 ± 0.052	1.215 ± 0.029	1.169 ± 0.025
	12	1.089 ± 0.044	1.247 ± 0.025	1.201 ± 0.029
	15	1.184 ± 0.049	1.320 ± 0.039	1.251 ± 0.025
WIDTH (CM)	**9**	0.828 ± 0.023	1.008 ± 0.009	0.979 ± 0.028
	12	0.901 ± 0.026	1.037 ± 0.018	1.026 ± 0.008
	15	1.027 ± 0.031	1.108 ± 0.004	1.069 ± 0.022
THICKNESS (CM)	**9**	0.374 ± 0.014	0.439 ± 0.015	0.400 ± 0.012
	12	0.421 ± 0.020	0.454 ± 0.018	0.435 ±0.015
	15	0.450 ± 0.018	0.492 ± 0.013	0.453 ± 0.015
BULK DENSITY (KG/M^3)	**9**	876.40 ± 34.05	811.50 ± 27.75	868.64 ± 32.20
	12	844.72 ± 25.80	726.96 ± 22.45	837.25 ± 22.45

	15	801.93 ± 23.34	688.64 ± 21.20	774.30 ± 20.23
A THOUSAND GRAIN	**9**	246.81 ± 7.40	340.08 ± 9.52	275.68 ± 7.95
MASS	**12**	286.98 ± 7.17	364.62 ± 9.12	292.78 ± 8.78
(G)	**15**	291.79 ± 9.04	375.36 ± 9.15	311.51 ± 8.65
GEOMETRIC MEAN DIAMETER (CM)	**9**	0.684 ± 0.012	0.813 ± 0.014	0.771 ± 0.015
	12	0.740 ± 0.023	0.855 ± 0.016	0.837 ± 0.018
	15	0.818 ± 0.022	0.896 ± 0.027	0.818 ± 0.022

Table 4.2: Analysis of Variance Table for Some Physical Properties of Maize

Source	DF	Property					
		Length	Width	Thickness	Bulk density	M1000	GMD
Replication	4	0.44 NS	0.02 NS	0.50 NS	0.31 NS	0.75 NS	0.65 NS
Moisture Content (Mc)	2	359.30 *	98.83 *	133.63 *	743.12 *	250.24 *	598.04*
Variety (V)	2	159.73*	75.08 *	246.28 *	1156.03 *	243.09 *	551.35*
Mc x V	4	60.91 *	0.45 NS	5.51 *	82.71 *	7.26 *	31.28*
Error	36						
Total	44						

NS: not significant; *: significant (i.e. at 5 %)

Table 4.3: Summary of Duncan Grouping for Some Physical Properties of Maize

PHYSICAL PROPERTIES

Variable	Length cm	Width cm	Thickness cm	Bulk density Kg/m^3	M1000 g	Geometric Mean dia cm
Moisture Content	15 %, 1.253a	15 %, 1.138a	15 %, 0.468a	9 %, 861.95a	15 %, 326.25a	15 %, 0.468a
	12 %, 1.201b	12 %, 1.017b	12 %, 0.437b	12 %, 812.50b	12 %, 314.69b	12 %, 0.811b
	9 %, 1.143c	9 %, 0.954c	9 %, 0.404c	15 %, 748.30c	9 %, 287.64c	9 %, 0.756c
Variety	TZB 1.272a	TZB 1.136a	TZB 0.462a	ACR 840.63a	TZB 360.32a	TZB 0.855a
	QPM 1.215b	QPM 1.050b	QPM 0.432b	QPM 826.67b,	QPM 293.33b	QPM 0.818b
	ACR 1.110c	ACR 0.923c	ACR 0.415c	TZB 755.45c	ACR 274.92c	ACR 0.747c

NB: Means with the same letter are not significantly different.

Similar trend in the decrease in mean values of length, width, thickness, thousand grain mass and geometric mean diameter when the moisture was decreased from 15 to 9 % was observed for the other two varieties (TZPB and QPM). Also the increase in bulk density as the moisture was decreased from 15 to 9 % was observed for these two varieties. Duncan multiple range grouping (table 4.3) indicates that the highest mean values of length, width thickness, one thousand grain mass and geometric mean diameter (1.253 cm, 1.138 cm, 0.468 cm, 326.25 g and 0.468 cm respectively) for the three varieties are obtained at the highest 15 % MC. The highest mean value of the bulk density (861.95 kg/m^3), however, is obtained at the lower 9 % moisture level. TZPB variety has the highest mean values of length, width thickness, one thousand grain mass and geometric mean diameter of 1.272 cm, 1.136 cm, 0.462 cm, 360.32 g and 0.855 cm, respectively. The least was the ACR variety with 1.110 cm, 0.923 cm, 0.415 cm, 274.92 g and 0.747 respectively, for the

parameters. The highest mean value for the bulk density (840.63 kg/m^3), however, is obtained for ACR variety. Interactions of moisture content and variety are significant for all the properties except the width. This means that the effect of these factors is not to be treated independently. The interaction for the differences between moisture content and varieties for the seed width is not significant. Hence this factor (width) can be judged independently for maize crop varieties considered.

4.2 Model Development Experiments

The analysis of variance to study the effects of the performance indices was performed for the model development data according to the experimental design as outlined in section 3.5. The statistical package (SAS) outputs for the performance indices of the validation data are shown in tables AII-2 – AII-6 in Appendix II. Mean values of performance indices are shown in tables 4.4 - 4.6. Effects of the independent variables on the performance indices as shown in table 4.7 are discussed below. Summary of DMRT and the statistical data summary of the performance indices are presented in tables 4.8 and 4.9 respectively.

4.2.1 Effect of cylinder speed on performance indices

Analysis of variance (table 4.7) shows that cylinder speed has significant effect on all the performance indices. At constant moisture content, feed rate and cylinder concave clearance of 9 %, 30 kg/min and 35 mm, respectively, the following trend was observed: As the cylinder speed was increased from 750 to 950 rpm, the output capacity, shelling

efficiency, cleaning efficiency, grain damage, and scatter loss values increased from 525.40 to 848.48 kg/h, 98.41 to 99.80 %, 87.43 to 95.18 %, 5.14 to 7.00 % and 13.85 to 15.46 %, respectively (table 4.4). Similar trend was observed at other moisture contents of 12 and 15 % (tables 4.5 and 4.6). The increase in shelling efficiency with increased speed is clear because as the frequency of impact and consequently rubbing action of the grains was more severe at increased speed, the shelling increases. These observations are corroborated by findings from other researchers (Oni and Ali, 1986; Anwar *et al*., 1991; Enaburekhan, 1994).

Table 4.4: Mean values of Performance indices: Model Development (9 % MC)

SPD	FDR	CLR	MC	Output,	Shelling	Cleaning	Damage	SCLoss
rpm	Kg/min	mm	%, wb	Kg/h	Eff, %	Eff, %	%	%
750	30	35	9	525.40	98.41	87.43	5.14	13.85
750	40	35	9	696.45	98.16	87.14	4.08	12.96
750	50	35	9	728.80	97.91	86.85	2.71	12.31
850	30	35	9	610.50	99.15	91.25	6.21	14.61
850	40	35	9	725.30	98.80	90.07	5.32	14.01
850	50	35	9	813.10	98.47	89.23	5.08	13.84
950	30	35	9	848.48	99.80	95.18	7.00	15.46
950	40	35	9	882.05	99.45	94.08	6.37	15.00

950	50	35	9	915.62	99.07	93.40	5.31	14.35
750	30	40	9	493.80	98.08	86.12	4.86	14.18
750	40	40	9	654.58	97.89	85.84	3.86	13.82
750	50	40	9	681.46	97.57	85.55	2.55	13.33
850	30	40	9	561.66	98.81	90.30	5.90	14.95
850	40	40	9	696.29	98.45	88.72	5.05	14.57
850	50	40	9	764.30	98.16	87.89	4.63	14.30
950	30	40	9	801.82	99.52	97.45	6.72	15.83
950	40	40	9	833.57	99.19	94.85	6.15	15.27
950	50	40	9	858.80	98.78	93.96	5.18	14.94
750	30	45	9	459.23	97.88	84.83	4.59	14.46
750	40	45	9	602.21	97.58	84.45	3.67	14.08
750	50	45	9	626.75	97.20	84.18	2.33	13.67
850	30	45	9	527.96	98.61	88.85	5.61	15.64
850	40	45	9	651.03	98.25	88.32	4.85	15.22
850	50	45	9	714.62	97.96	87.75	4.32	14.74
950	30	45	9	745.70	99.32	93.76	6.55	16.08
950	40	45	9	783.50	98.99	92.38	5.84	15.74
950	50	45	9	807.30	98.58	91.78	4.92	15.30

SPD=Speed, FDR= Feed rate, CLR= concave clearance, MC= Moisture content

Table 4.5: Mean values of Performance indices: Model Development (12 % MC)

SPD	**FDR**	**CLR**	**MC**	**Output**	**Shelling**	**Cleang**	**Damage**	**SCLoss**
rpm	kg/min	Mm	%, wb	Kg/h	Eff, %	Eff, %	%	%
750	30	35	12	480.50	98.04	83.95	3.97	13.30
750	40	35	12	529.25	97.76	82.85	3.65	12.50
750	50	35	12	602.60	97.46	81.94	3.08	12.10
850	30	35	12	520.70	98.65	90.60	4.79	14.27
850	40	35	12	670.52	98.32	88.80	4.41	13.75
850	50	35	12	705.60	98.02	88.12	4.15	13.28

950	30	35	12	616.74	99.34	90.42	5.60	14.65
950	40	35	12	740.85	99.08	94.01	5.26	13.52
950	50	35	12	767.05	98.70	92.75	4.84	13.00
750	30	40	12	451.66	97.83	82.38	3.75	14.62
750	40	40	12	497.50	97.57	81.36	3.46	14.19
750	50	40	12	571.27	97.27	81.02	2.32	13.73
850	30	40	12	491.01	98.31	89.49	4.38	15.50
850	40	40	12	637.00	98.07	88.25	4.14	15.12
850	50	40	12	666.84	97.82	87.15	3.73	14.69
950	30	40	12	585.90	99.05	94.46	5.15	17.09
950	40	40	12	705.17	98.81	93.95	4.73	16.48
950	50	40	12	727.93	98.41	90.47	4.66	15.47
750	30	45	12	426.81	97.34	81.44	3.67	14.02
750	40	45	12	470.14	97.05	80.22	3.11	13.74
750	50	45	12	530.10	96.78	79.80	2.14	13.28
850	30	45	12	459.10	97.83	87.14	4.18	15.22
850	40	45	12	605.15	97.60	86.60	3.84	14.83
850	50	45	12	628.20	97.30	85.90	3.47	14.18
950	30	45	12	550.75	98.68	92.96	4.84	15.02
950	40	45	12	662.86	98.35	91.76	4.57	14.64
950	50	45	12	680.60	97.92	90.96	4.30	14.10

Table 4.6: Mean values of Performance indices: Model Development (15 % MC)

SPD	**FDR**	**CLR**	**MC**	**Output,**	**Shelling**	**Cleaning**	**Damage**	**SCLoss**
rpm	Kg/min	Mm	%, wb	Kg/h	Eff, %	Eff, %	%	%
750	30	35	15	446.15	97.59	79.94	3.70	12.70
750	40	35	15	480.08	97.33	78.79	3.30	12.25
750	50	35	15	556.80	97.02	78.87	3.00	11.83

850	30	35	15	458.30	98.14	86.80	4.35	13.59
850	40	35	15	585.60	97.87	85.50	4.05	13.12
850	50	35	15	645.16	97.56	84.47	3.73	12.84
950	30	35	15	574.46	98.92	93.25	4.76	14.00
950	40	35	15	688.80	98.58	91.57	4.40	13.28
950	50	35	15	740.15	98.16	90.25	4.05	12.70
750	30	40	15	385.94	97.34	78.75	3.19	13.07
750	40	40	15	440.80	97.08	77.17	2.98	12.80
750	50	40	15	502.70	96.78	77.30	3.10	12.56
850	30	40	15	417.36	97.92	85.50	4.14	13.86
850	40	40	15	554.20	97.58	84.26	3.84	13.42
850	50	40	15	600.15	97.32	82.58	3.57	13.10
950	30	40	15	540.60	98.65	91.62	4.38	14,33
950	40	40	15	620.40	98.32	90.43	4.07	14.00
950	50	40	15	655.14	97.90	89.75	3.86	13.72
750	30	45	15	370.60	96.95	77.56	3.20	13.84
750	40	45	15	423.00	96.60	76.92	2.85	13.30
750	50	45	15	472.30	96.29	76.08	2.03	13.01
850	30	45	15	397.12	97.58	84.16	4.01	14.18
850	40	45	15	525.42	97.29	83.75	3.69	13.82
850	50	45	15	560.40	96.90	82.71	3.40	13.50
950	30	45	15	523.15	98.30	90.25	4.26	14.78
950	40	45	15	590.80	97.90	89.23	3.85	14.26
950	50	45	15	625.70	97.52	88.69	3.60	13.90

Table 4.7: Summary of the Analyses of Variance for the Effects of Variables on the Performance Indices: Model Development

Source	DF	Output	Shelling	Cleaning	Damage	Loss

Replication, R	2	0.23 ns	1.37 ns	2.10 ns	3.87 ns	3.88 ns
Speed, S	2	4105.58*	669.59 *	10294.1*	94809.20*	59027.50*
Feed rate, F	2	2602.64*	166.20 *	273.81*	38193.4 *	26210.0*
Concave clearance, C	2	753.54 *	167.34 *	392.10 *	9827.87 *	35870.00*
Moisture Content, M	2	3647.73*	340.70 *	2699.70*	60500.90*	43142.00*
S*F	4	65.79 *	0.94 ns	8.19 *	1263.51*	183.07 *
S*C	4	3.32 *	0.25 ns	24.02*	8.21 **	1209.86*
S*M	4	87.92 *	0.66 ns	179.47 *	4021.20 *	1155.21*
F*C	4	5.72 *	0.13 ns	7.23 *	90.67 *	337.90 *
F*M	4	3.78 *	0.16 ns	3.73 *	3802.66*	231.43 *
C*M	4	9.10 *	2.31 ns	8.35 *	81.36 *	7478.12*
S*F*M	8	0.69 ns	0.05 ns	7.62 *	75.62 *	80.51 *
S*F*C	8	46.75 *	0.07 ns	8.35 *	405.25 *	84.26 *
S*C*M	8	0.57 ns	0.14 ns	9.12 *	68.93 *	809.50 *
F*C*M	8	0.29 ns	0.03 ns	4.08 *	67.98 *	61.17 *
S*F*C*M	16	0.98 ns	0.06 ns	6.61 *	91.66 *	67.36 *
Error	160					
Total	242					

ns: not significant; *: significant (i.e. at 5%).

Table 4.8 Summary of Duncan Grouping for Model Development Data

Variable	Performance Indices				
	Output Capacity Kg/h	Shelling Efficiency %	Cleaning Efficiency %	Grain Damage %	Scatter Loss %
Speed rpm	950, 706.44 a	950, 98.71 a	950, 92.36 a	950, 5.01a	950, 14.70 a
	850, 599.73 b	850, 98.03 b	850, 87.19 b	850, 4.40 b	850, 14.23 b
	750, 522.48 c	750, 97.44 c	750, 81.80 c	750, 3.34 c	750, 13.31 c
Feed Rate kg/min	50, 672.20 a	30, 98.37 a	30, 87.99 a	30, 4.77 a	30, 14.56 a
	40, 627.87 b	40, 98.07 b	40, 87.08 b	40, 4.27 b	40, 14.06 b
	30, 528.57 c	50, 97.73 c	50, 86.27 c	50, 3.71 c	50, 13.62 c
Cylinder Concave Clearance m	35, 650.18 a	35, 98.36 a	35, 88.06 a	30, 4.53 a	45, 4.41 a
	40, 607.33 b	40, 98.09 b	40, 87.28 b	40, 4.24 b	30, 14.39 b
	45, 571.13 c	45, 97.72 c	45, 86.02 c	45, 3.99 b	35, 13.45 c
Moisture Content %	9, 704.00 a	9, 98.52 a	9, 89.69 a	9, 4.99 a	9, 14.53 a
	12, 591.91 b	12, 98.05 b	12, 87.36 b	12, 4.08 b	12, 14.31 b
	15, 532.64 c	15, 97.61 c	15, 84.30 c	15, 3.68 c	15, 13.40 c

NB: Means with the same letter are not significantly different

Table 4.9: Statistical Information Summary on the Model Development Data for Performance Indices of Maize dehusker Sheller

Performance Index	R^2	RMSE	CV	Mean
Output	0.9931	12.9749	2.1286	609.55, kg/h
Shelling	0.9443	0.2226	0.2270	98.06, %
Cleaning	0.9944	0.4680	0.5372	87.12, %
Damage	0.9996	0.0246	0.5789	4.25, %
Loss	0.9995	0.0260	0.1853	14.08, %

When other factors are kept constant, the increase in grain damage as the speed increases could be explained by the fact that at higher speeds, there is no much build up of the straw-grain material in the threshing chamber that could provide the needed cushioning effect on the grains. As such, the grain damage increases. These observations are corroborated by findings from other researchers (Oni and Ali, 1986; Anwar *et al*., 1991; Enaburekhan, 1994; El-Haddad, 2000; Fernando *et al*., 2004; Vajasit and Solokha, 2006 and Sseiz *et al*., 2007). The increase in cleaning efficiency with increasing cylinder speed, all other factors being constant, could be attributed to the fact that according to the design, the cleaning fan pulley is directly being driven by the cylinder pulley. Hence an increase in cylinder speed could enhance higher cleaning. The increase in grain losses higher speeds may be due to the fact that at increased shelling rate there was no corresponding increase in separation rate leading to increased losses of grain. Duncan grouping shows that the highest mean value for output, shelling efficiency, cleaning efficiency, grain damage, and scatter loss of 706.44 kg/hr, 98.71 %, 92.36 %, 5.01 %, and 14.70 %, respectively, was obtained at the highest speed of 950 rpm.

4.2.2 Effect of crop feed rate on performance indices

Analysis of variance (table 4.7) shows that the feed rate has significant effect on all the performance indices. At constant moisture content, cylinder speed and concave clearance of 9 %, 850 rpm and 35 mm, respectively, the following trend was observed: As the feed rate was increased from 30 to 50 kg/min, the shelling efficiency, cleaning efficiency, grain damage, and scatter loss values decreased from 99.15 to 98.47 %, 91.25 to 90.07 %, 6.21

to 5.32 % and 14.61 to 14.01 %, respectively (table 4.4). The output capacity, however, had a corresponding increase from 610.50 to 725.30 kg/h. Similar trend was observed at other moisture contents of 12 and 15 % (tables 4.5 and 4.6). The decrease in shelling as a result of increased feed rate may be attributed to the fact that at higher feed rates, there would be crop stream material build up. This may tend to reduce the probability of detachment of the grain and hence decrease the shelling. The significant decrease in grain damage at higher feed rates, keeping other factors constant, could be due to the dense crop stream material to cushion the beater impacts thus shelving the grains from the beating impulse. The decrease in cleaning efficiency with increased feed rates might have happened due to the excessive presence of chaff to be blown, which is a reality associated with higher feed rates. This could also be attributed to the higher volume of material at higher feed rates, which in turn reduces the fan performance. This agrees with Anwar *et al*., (1991). The increase in output with an increase in feed rate, all other factors being constant could be due to the fact that output is a percentage or fraction of the feed rate. The cob/grain ratio and separation rate accounting for the difference. Hence it is expected to increase when the feed rate is increased. Duncan grouping shows that the highest mean value for shelling efficiency, cleaning efficiency, grain damage, and scatter loss of 98.37 %, 87.99 %, 4.77 %, and 14.56 %, respectively, was obtained at the lowest feed rate of 30 kg/min. Highest mean value for output capacity of 672.20 kg/h was obtained at the highest feed rate of 50 kg/min.

4.2.3 Effect of cylinder - concave clearance on performance indices

Analysis of variance (table 4.7) shows that the concave clearance has significant effect on all the performance indices. At constant moisture content, cylinder speed and feed rate of 9 %, 850 rpm and 30 kg/min, respectively, the following trend was observed: As the concave clearance was increased from 35 to 45 mm, the output capacity, shelling efficiency, cleaning efficiency and grain damage, values decreased from 610.50 to 527.96 kg/min, 99.15 to 98.61 %, 91.25 to 88.05 %, and 6.21 to 5.61 %, respectively (table 4.4). The scatter loss, however, had a corresponding increase from 14.61 to 15.64 %. Similar trend was observed at other moisture contents of 12 and 15 % (tables 4.5 and 4.6). The decrease in shelling efficiency with increased concave clearance may be due to the reason that at higher clearance there is an increased gap which may not only allow the escape of the crop from the beats of the pegs but also reduce the resistance between the cobs and the drum. These mean insufficient force and frequency of impacts, the result of which is decreased shelling. This agrees with Sudgan *et al*., (2005). The decrease in grain damage with increase in concave clearance, all other factors kept constant, may be due to the fact that with increased cross sectional area due to increased clearance, the impact force on the free grain before separation reduces. This might have caused the decrease in damage. At higher clearance, there is a tendency for spill over straw- chaff stream. This could reduce the cleaning. The increase in scatter losses with an increase in concave clearance may be due to the reason that at higher clearance, the separation rate could not match the crop stream volume increase. Thus the free grain not separated within the time goes out as loss. Duncan grouping shows that the highest mean value for output capacity, shelling efficiency, cleaning efficiency and grain damage of 650.18 kg/h 98.36 %, 88.06 %

and 4.53 %, respectively, was obtained at the lowest concave clearance of 35 mm. Highest mean value for scatter loss of 14.41 % was obtained at the highest concave clearance of 45 mm.

4.2.4 Effect of grain moisture content on performance indices

Analysis of variance (table 4.7) shows that the grain moisture content has significant effect on all the performance indices. At constant feed rate, cylinder speed and concave clearance of 40 kg/min, 950 rpm and 35 mm, respectively, the following trend was observed: As the grain moisture content was reduced from 15 to 9 %, the output capacity, shelling efficiency, cleaning efficiency, grain damage and scatter loss values increased from 688.80 to 882.05 kg/h, 98.58 to 99.45 %, 91.57 to 94.08 %, 4.90 to 6.37 % and 13.28 to 15.00 (table 4.5 and 4.6). Similar trend was observed at other factor combinations. For parameters that are needed to be maximized (shelling, cleaning and output), best values are obtained at lower moisture. On the other hand, Parameters that need to be minimized (grain loss and damage) are at disadvantage with lower moisture during operations. At higher moisture, the high grain adhesion to the cob, decreases the shelling rate. At lower moisture, less impact force is required to detach the grain from the cob, hence higher shelling. With less moisture, the crop stream build up tend to be less. Separation could thus be enhanced and therefore an increased output. Grain damage is high at lower moisture content. This agrees with Oluwale *et al.,* (2007). A possible explanation is that at higher moisture, the grain tends to be more elastic and hence less brittle. At lower moisture, it becomes more brittle and therefore yields easier to beater

impacts. Duncan grouping shows that the highest mean value for output, shelling efficiency, cleaning efficiency, grain damage, and scatter loss of 704.00 kg/hr, 98.52 %, 89.69 %, 4.99 %, and 14.53 %, respectively, was obtained at the lowest grain moisture content of 9 % (wet basis).

4.3 Model Validation Experiments

The statistical package (SAS) outputs for the performance indices of the validation data are shown in tables AII-7 – AII-11 in Appendix II.. Mean values of performance indices are shown in tables 4.10 - 4.12. Effects of the independent variables on the performance indices as shown in table 4.13 are discussed below. Summary of Duncan Grouping and the statistical data summary of the performance indices are presented in tables 4.14 and 4.15 respectively.

4.3.1 Effect of cylinder speed on performance indices

Analysis of variance (table 4.13) shows that cylinder speed has significant effect on all the performance indices. At constant moisture content, feed rate and cylinder concave clearance of 9 %, 30 kg/min and 35 mm, respectively, the following trend was observed: As the cylinder speed was increased from 750 to 950 rpm, the output capacity, shelling efficiency, cleaning efficiency, grain damage, and scatter loss values increased from 560.34 to690.97 kg/h, 98.52 to 99.84 %, 96.85 to 97.59 %, 4.83 to 5.70 % and 16.32 to 17.05 %, respectively (table 4.10). Similar trend was observed at other moisture contents

of 12 and 15 % (tables 4.11 and 4.12). The increase in shelling efficiency with increased speed is clear because as the frequency of impact and consequently rubbing action of the grains was more severe at increased speed, the shelling increases. These observations are corroborated by findings from other researchers (Oni and Ali, 1986; Anwar *et al*., 1991; Enaburekhan, 1994).

Table 4.10: Mean values of Performance indices: Model Validation (9 % MC)

SPD	FDR	CLR	MC	Output,	Shelling	Cleaning	Damage	SCLoss
rpm	Kg/min	mm	%, wb	Kg/h	Eff, %	Eff, %	%	%
750	30	35	9	560.34	98.52	96.85	4.83	16.32
750	40	35	9	615.61	98.43	96.35	4.53	15.71
750	50	35	9	706.08	98.17	96.40	4.26	15.24
850	30	35	9	650.63	99.15	97.13	5.12	16.73
850	40	35	9	735.64	98.95	96.85	5.03	16.43
850	50	35	9	846.48	98.54	96.53	4.69	16.03
950	30	35	9	690.97	99.84	97.59	5.70	17.05
950	40	35	9	729.39	99.56	97.02	5.33	16.61
950	50	35	9	844.69	99.28	97.07	4.70	16.24
750	30	40	9	542.32	98.37	95.46	4.39	16.70
750	40	40	9	577.81	98.28	94.76	4.28	15.85
750	50	40	9	637.34	98.04	94.11	3.98	15.44
850	30	40	9	632.18	98.67	96.40	4.93	17.02
850	40	40	9	679.66	98.47	95.84	4.65	16.79
850	50	40	9	715.32	98.32	95.49	4.50	16.32
950	30	40	9	680.23	99.47	97.03	5.19	17.43

950	40	40	9	716.69	99.19	96.96	5.01	16.92
950	50	40	9	763.40	99.03	96.22	4.84	16.51
750	30	45	9	538.21	98.24	95.05	4.22	16.99
750	40	45	9	564.87	98.12	94.02	4.06	16.41
750	50	45	9	607.23	97.92	93.78	3.32	15.96
850	30	45	9	614.79	98.69	95.80	4.51	17.32
850	40	45	9	658.18	98.50	95.05	4.21	17.05
850	50	45	9	688.23	98.18	94.84	3.92	16.75
950	30	45	9	673.84	99.27	96.16	4.70	17.62
950	40	45	9	689.90	98.95	95.41	4.45	17.48
950	50	45	9	737.31	98.67	93.50	3.95	17.11

Table 4.11: Mean values of Performance indices: Model Validation (12 % MC)

SPD	**FDR**	**CLR**	**MC**	**Output**	**Shellg**	**Cleang**	**Damage**	**SCLoss**
rpm	Kg/min	Mm	%, wb	Kg/h	Eff, %	Eff, %	%	%
750	30	35	12	514.05	98.30	95.86	4.21	14.06
750	40	35	12	546.32	98.00	95.28	3.87	13.64
750	50	35	12	584.36	97.83	94.92	3.64	13.32
850	30	35	12	567.56	98.67	96.77	4.40	14.44
850	40	35	12	612.77	98.52	96.27	4.26	14.07
850	50	35	12	676.87	98.25	95.95	4.18	13.74
950	30	35	12	650.53	99.19	97.25	4.74	14.69
950	40	35	12	671.61	98.99	96.86	4.42	14.33
950	50	35	12	687.26	98.86	96.63	4.24	14.03
750	30	40	12	513.89	98.18	95.11	3.88	14.36
750	40	40	12	541.63	97.87	94.69	3.55	13.89
750	50	40	12	557.26	97.63	94.06	3.27	13.71
850	30	40	12	559.93	98.52	96.06	4.20	14.67
850	40	40	12	599.92	98.29	95.45	3.80	14.31

850	50	40	12	613.29	98.05	94.90	3.51	13.93
950	30	40	12	614.25	98.94	95.61	4.55	14.76
950	40	40	12	671.48	98.70	95.23	4.11	14.54
950	50	40	12	697.19	98.46	94.86	3.77	14.00
750	30	45	12	502.98	97.63	94.77	3.50	14.77
750	40	45	12	523.00	97.35	94.46	3.21	14.30
750	50	45	12	540.33	97.12	93.66	3.02	14.03
850	30	45	12	565.85	97.95	95.38	3.74	14.93
850	40	45	12	585.46	97.72	94.88	3.51	14.66
850	50	45	12	609.71	97.50	94.46	3.15	14.32
950	30	45	12	635.58	98.59	95.82	3.99	15.13
950	40	45	12	661.30	98.27	95.19	3.66	14.85
950	50	45	12	676.11	97.93	93.17	3.37	14.56

Table 4.12: Mean values of Performance indices: Model Validation (15 % MC)

SPD	**FDR**	**CLR**	**MC**	**Output,**	**Shelling**	**Cleaning**	**Damage**	**SCLoss**
rpm	Kg/min	Mm	%, wb	Kg/h	Eff, %	Eff, %	%	%
750	30	35	15	420.83	97.70	92.82	3.86	13.64
750	40	35	15	450.06	97.32	92.38	3.55	12.33
750	50	35	15	473.58	97.01	92.01	3.28	11.76
850	30	35	15	466.95	98.34	93.09	4.15	13.93
850	40	35	15	474.67	98.02	92.67	4.01	12.60
850	50	35	15	498.88	97.62	92.32	3.84	12.33
950	30	35	15	501.98	98.80	93.78	4.49	14.08
950	40	35	15	532.24	98.56	93.20	4.16	13.72
950	50	35	15	558.34	98.25	92.88	3.30	13.44
750	30	40	15	392.75	97.59	92.34	3.52	13.72
750	40	40	15	429.72	97.34	92.02	3.22	12.49

750	50	40	15	453.36	96.72	91.62	2.96	12.16
850	30	40	15	437.68	97.98	92.66	3.88	13.88
850	40	40	15	454.73	97.78	92.19	3.42	13.34
850	50	40	15	473.84	97.53	91.75	3.16	12.86
950	30	40	15	491.89	98.54	93.13	4.21	14.22
950	40	40	15	511.66	98.23	92.81	3.80	14.02
950	50	40	15	536.59	97.89	92.31	3.42	13.50
750	30	45	15	378.11	97.02	91.68	3.13	14.04
750	40	45	15	403.37	96.76	91.21	2.92	12.85
750	50	45	15	424.19	96.52	90.54	2.57	12.36
850	30	45	15	444.34	97.43	92.10	3.43	14.20
850	40	45	15	429.91	97.20	91.59	3.10	13.55
850	50	45	15	475.40	96.95	91.05	2.87	13.24
950	30	45	15	463.69	98.01	91.83	3.73	14.32
950	40	45	15	481.91	97.67	91.36	3.29	14.21
950	50	45	15	500.41	97.38	90.86	2.98	13.68

Table 4.13: Summary of the Analyses of Variance for the Effects of Variables on the Performance Indices: Validation Experiment

Source	DF	Output	Shelling	Cleaning	Damage	Loss
Replication, R	2	1.71 ns	1.29 ns	0.61 ns	12.76 *	1.51 ns
Speed, S	2	1384.70*	23908.5 *	1227.71*	1870.16 *	14665.5 *
Feed rate, F	2	514.96 *	6623.14*	1575.90*	2216.61 *	16568.6 *
Concave clearance, C	2	213.90 *	10068.2*	4202.34*	3358.21 *	7264.54 *
Moisture Content, M	2	4606.97*	27978.3*	23900.6*	7104.23 *	222982 *
S*F	4	0.45 ns	8.95 *	18.61 *	31.36 *	557.82 *

S*C	4	3.98 *	122.63 *	96.41 *	25.82 *	36.70 *
S*M	4	42.83 *	111.34 *	56.72 *	20.49 *	659.36 *
F*C	4	20.84 *	1.58 ns	72.95 *	5.47 *	68.15 *
F*M	4	41.20 *	61.72 *	8.92 *	13.16 *	512.83 *
C*M	4	19.76 *	441.25 *	98.47 *	8.54 *	79.65 *
S*F*M	8	1.74 *	29.85 *	32.48 *	18.69 *	35.29 *
S*F*C	8	2.99 *	27.49 *	6.95 *	6.41 *	205.44 *
S*C*M	8	3.05 *	36.73 *	60.07 *	8.56 *	52.69 *
F*C*M	8	8.28 *	24.89 *	10.99 *	18.81 *	38.35 *
S*F*C*M	16	1.53 *	5.75 *	11.74 *	6.11 *	18.70 *
Error	160					
Total	242					

ns: not significant; *: significant (i.e. at 5%); **: highly significant (i.e. at 1%);

Table 4:14 Summary of Duncan Grouping for Validation Data

Variable	Performance Indices				
	Output Capacity Kg/h	Shelling Efficiency %	Cleaning Efficiency %	Grain Damage %	Scatter Loss %
Speed rpm	950, 682.24a	950, 98.69 a	950, 94.81 a	950, 4.22 a	950, 15.15 a
	850, 584.03 b	850, 98.14 b	850, 94.57 b	850, 4.01 b	850, 14.79 b
	750, 518.50 c	750, 97.70 c	750, 93.93 c	750, 3.67 c	750, 14.30 c
Feed	50, 614.19 a	30, 98.43 a	30, 94.94 a	30, 4.27 a	30, 15.22 a

Rate kg/min	40, 575.91 b	40, 98.18 b	40, 94.45b	40, 3.98 b	40, 14.70 b
	30, 544.68 c	50, 97.91 c	50, 93.92 c	50, 3.65 c	50, 14.32 c
Cylinder Concave Clearance m	35, 602.55 a	35, 8.47 a	35, 95.29 a	35, 4.33 a	45, 15.06 a
	40, 573.93 b	40, 98.23 b	40, 94.41 b	40, 3.99 b	40, 14.72 b
	45, 558.30 c	45, 97.84 c	45, 93.62 c	45, 3.57 c	35, 14.46 c
Moisture Content %	9, 670.27 a	9, 98.70 a	9, 95.84 a	9, 4.54 a	15, 16.59 a
	12, 599.28 b	12, 98.20 b	12, 95.32 b	12, 3.84 b	12, 14.29 b
	15, 465.23 c	15, 97.64 c	15, 92.16 c	15, 3.49 c	15, 13.35 c

NB: Means with the same letter are not significantly different.

Table 4.15: Statistical Information Summary on the validation experiment for Performance Indices of Maize dehusker Sheller

Performance Index	R^2	RMSE	CV	Mean
Output	0.9887	2.3877	13.8069	578.26
Shelling	0.9988	0.0292	0.0286	98.18
Cleaning	0.9975	0.1229	0.1160	94.44
Damage	0.9947	1.4761	0.0585	3.97
Loss	0.9997	0.2155	0.0317	14.75

When other factors are kept constant, the increase in grain damage as the speed increases could be explained by the fact that at higher speeds, there is no much build up of the straw-grain material in the threshing chamber that could provide the needed cushioning effect on the grains. As such, the grain damage increases.These observations are corroborated by findings from other researchers (Oni and Ali, 1986; Anwar *et al*., 1991; Enaburekhan, 1994; El-Haddad, 2000; Fernando *et al*., 2004; Vajasit and Solokha,

2006 and Sseiz *et al*., 2007). The increase in cleaning efficiency with increasing cylinder speed, all other factors being constant, could be attributed to the fact that according to the design, the cleaning fan pulley is directly being driven by the cylinder pulley.Hence an increase in cylinder speed could enhance higher cleaning. The increase in grain losses higher speeds may be due to the fact that at increased shelling rate there was no corresponding increase in separation rate leading to increased losses of grain. Duncan grouping shows that the highest mean value for output, shelling efficiency, cleaning efficiency, grain damage, and scatter loss of 682.24 kg/hr, 98.69 %, 94.81 %, 4.22 %, and 15.15 %, respectively, was obtained at the highest speed of 950 rpm.

4.3.2 Effect of crop feed rate on performance indices

Analysis of variance (table 4.13) shows that the feed rate has significant effect on all the performance indices. At constant moisture content, cylinder speed and concave clearance of 9 %, 850 rpm and 35 mm, respectively, the following trend was observed: As the feed rate was increased from 30 to 50 kg/min, the shelling efficiency, cleaning efficiency, grain damage, and scatter loss values decreased from 99.15 to 98.54 %, 97.13 to 96.53 %, 5.12 to 4.69 % and 16.73 to 16.03 %, respectively (table 4.10). The output capacity, however, had a corresponding increase from 846.48 to 650.63 kg/h. Similar trend was observed at other moisture contents of 12 and 15 % (tables 4.11 and 4.12). The decrease in shelling as a result of increased feed rate may be attributed to the fact that at higher feed rates, there would be crop stream material build up. This may tend to reduce the probability of detachment of the grain and hence decrease the shelling. The significant decrease in

grain damage at higher feed rates, keeping other factors constant, could be due to the dense crop stream material to cushion the beater impacts thus shelving the grains from the beating impulse. The decrease in cleaning efficiency with increased feed rates might have happened due to the excessive presence of chaff to be blown, which is a reality associated with higher feed rates. This could also be attributed to the higher volume of material at higher feed rates, which in turn reduces the fan performance. This agrees with Anwar *et al*., (1991). The output capacity increased with an increase in feed rate, all other factors being constant. This could be due to the fact that output is a percentage or fraction of the feed rate. The cob/grain ratio and separation rate accounting for the difference. Therefore it increases with increase in feed rate. Duncan grouping shows that the highest mean value for shelling efficiency, cleaning efficiency, grain damage, and scatter loss of 98.43 %, 94.94 %, 4.27 %, and 15.22 %, respectively, was obtained at the lowest feed rate of 30 kg/min. Highest mean value for output capacity of 614.19 kg/h was obtained at the highest feed rate of 50 kg/min.

4.3.3 Effect of cylinder - concave clearance on performance indices

Analysis of variance (table 4.13) shows that the concave clearance has significant effect on all the performance indices. At constant moisture content, cylinder speed and feed rate of 9 %, 850 rpm and 30 kg/min, respectively, the following trend was observed: As the concave clearance was increased from 35 to 45 mm, the output capacity, shelling

efficiency, cleaning efficiency and grain damage, values decreased from 650.63 to 614.79 kg/min, 99.15 to 98.69 %, 97.13 to 95.80 %, and 5.12 to 4.51 %, respectively (table 4.10). The scatter loss, however, had a corresponding increase from 16.73 to 17.32 %. Similar trend was observed at other moisture contents of 12 and 15 % (tables 4.11 and 4.12). The decrease in shelling efficiency with increased concave clearance may be due to the reason that at higher clearance there is an increased gap which may not only allow the escape of the crop from the beats of the pegs but also reduce the resistance between the cobs and the drum. These mean insufficient force and frequency of impacts, the result of which is decreased shelling. This agrees with Sudgan *et al*., (2005). The grain damage decreased with increase in concave clearance, all other factors kept constant. Of course with increased cross sectional area due to increased clearance, the impact force on the free grain before separation reduces. That may decrease the damage. At higher clearance, there is a tendency for spill over straw- chaff stream. This could reduce the cleaning. The increase in scatter losses with an increase in concave clearance may be due to the reason that at higher clearance, the separation rate could not match the crop stream volume increase. Thus the free grain not separated within the time goes out as loss. Duncan grouping shows that the highest mean value for output capacity, shelling efficiency, cleaning efficiency and grain damage of 602.55 kg/h 98.47 %, 95.29 % and 4.33 %, respectively, was obtained at the lowest feed rate of 30 kg/min. Highest mean value for scatter loss of 15.06 % was obtained at the highest concave clearance of 45 mm.

4.3.4 Effect of grain moisture content on performance indices

Analysis of variance (table 4.13) shows that the grain moisture content has significant effect on all the performance indices. At constant feed rate, cylinder speed and concave clearance of 40 kg/min, 950 rpm and 35 mm, respectively, the following trend was observed: As the grain moisture content was reduced from 15 to 9 %, the output capacity, shelling efficiency, cleaning efficiency, grain damage and scatter loss values increased from 532.24 to729.39 kg/h, 98.56 to 99.56 %, 93.20 to 97.02 %, 4.16 to 5.33 % and 13.72 to 16.61 (table 4.10). Similar trend was observed at other factor combinations (tables 4.11 and 4.12). For parameters that are needed to be maximized (shelling, cleaning and output), best values are obtained at lower moisture. On the other hand, Parameters that need to be minimized (grain loss and damage) are at disadvantage with lower moisture during operations. At higher moisture, the high grain adhesion to the cob, decreases the shelling rate. At lower moisture, less impact force is required to detach the grain from the cob, hence higher shelling. With less moisture, the crop stream build up tend to be less. Separation could thus be enhanced and therefore an increased output. Grain damage is high at lower moisture content. This agrees with Oluwale *et al.,* (2007). A possible explanation is that at higher moisture, the grain tends to be more elastic and hence less brittle. At lower moisture, it becomes more brittle and therefore yields easier to beater impacts. Duncan grouping shows that the highest mean value for output, shelling efficiency, cleaning efficiency, grain damage, and scatter loss of 670.27 kg/hr, 98.70 %, 95.84 %, 4.54 %, and 16.59 %, respectively, was obtained at the lowest grain moisture content of 9 % (wet basis).

4.4 Shelling Efficiency Model

From section 3.0, the following pi terms were determined

$\pi_1 = \lambda_S C$, $\pi_2 = \frac{\rho_g V C^2}{F_r}$ and $\pi_3 = \frac{C}{DM}$ Where the symbols take their established definitions. Plots of π_1 against π_2 holding π_3 constant and π_1 against π_3 holding π_2 constant were performed. The results are as shown in figures 4.1 and 4.2. Additional supplementary equation relating π_1 with π_2 was generated by holding π_3 constant at different value from its magnitude in the original component equation (figure 4.3). From the figures, 4.1- 4. 3, the following component equations were produced

$$\pi_1 = 0.061\ \pi_2^{0.516} \quad (4.1)$$

$$\pi_1 = 0.163\ \pi_3^{0.69} \quad (4.2)$$

$$\pi_1 = 0.065\ \pi_2^{0.491} \quad (4.3)$$

From the analysis by Murphy (1950) as explained in chapter 2.0, for product validity (equation 2.47), then:

$$A\bar{\pi}_2^{\,m} = 0.061\ (16.505)^{0.516} = 0.2592 \quad (4.4)$$

$$C\bar{\pi}_2^{\,m} = 0.065\ (16.261)^{0.491} = 0.2556 \quad (4.5)$$

substituting, $$\frac{0.061\ \pi_2^{0.516}}{0.2592} = \frac{0.065\ \pi_2^{0.491}}{0.2556} \quad (4.6)$$

Or $$0.0156\ \pi_2^{0.516} = 0.0168\ \pi_2^{0.491} \quad (4.7)$$

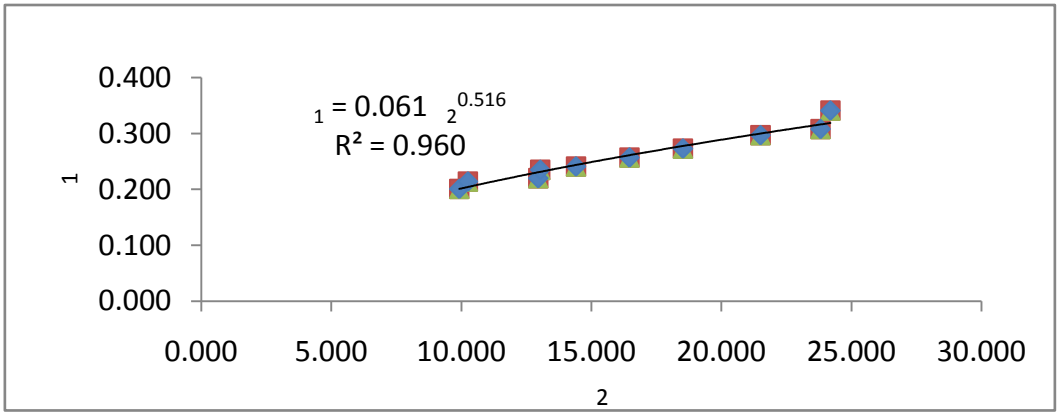

Fig 4.1 Plot of π_1 against π_2 for shelling

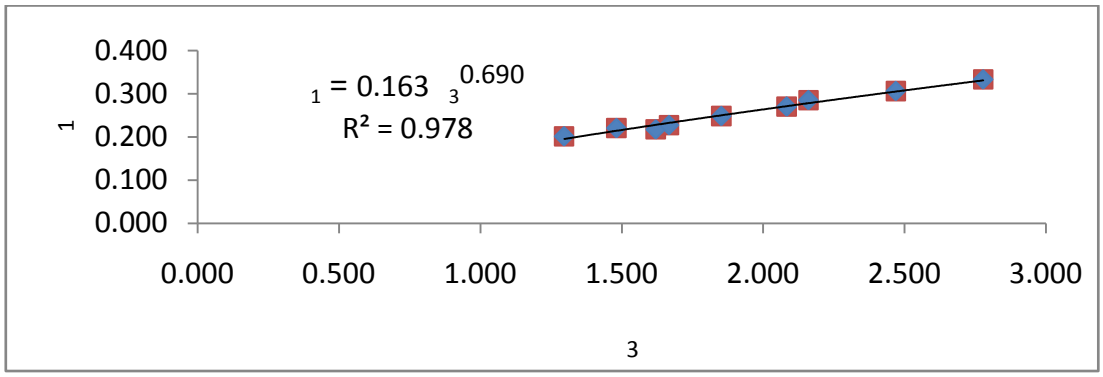

Fig 4.2 Plot of π_1 against π_3 for shelling

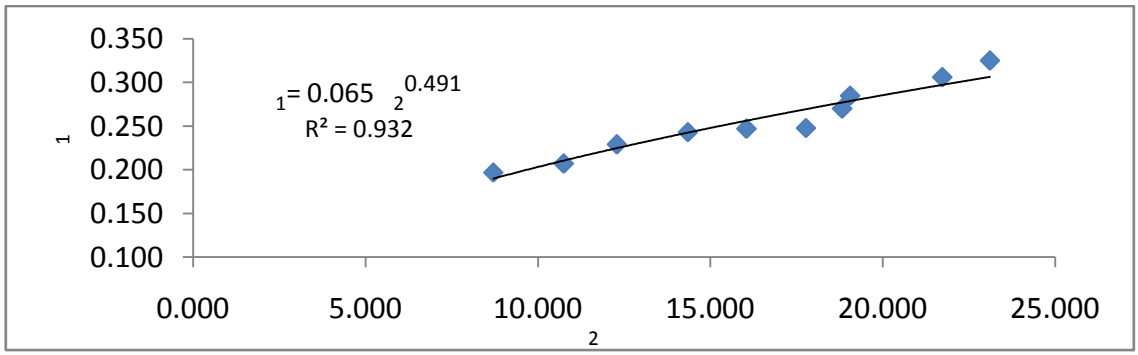

Fig 4.3 Plot of π_1 against π_2 for shelling (supplementary data)

Substituting any arbitrary value of π_2, say 16.0, the right hand side (0.0652)is almost the same as the left hand side (0.0654). Hence this makes the combination of the component equations by multiplication valid. The prediction equation is thus formed by the product combination of the component equations divided by the constant (see equation 2.40). Substituting values and rearranging (see detailed computation in Appendix III), the prediction equation for shelling parameter is thus established:

$$\lambda_S = 0.0385\, C^{0.73} \left(\frac{\rho_g V}{F_r}\right)^{0.52} \left(\frac{1}{DM}\right)^{0.69} \qquad (4.8)$$

From earlier literature review in section 2.6.1, it was established that at the end of the shelling length l, the shelling loss, say V_t, was given by equation 2.23**,** Hence the shelling efficiency, η_S, becomes

$$\eta_S = (1 - V_t) \text{ x } 100\ \% \ = \ (1 - e^{-\lambda_S l}) \text{ x } 100\ \% \qquad (4.9)$$

4.4.1 Shelling efficiency model evaluation

In evaluation of the shelling efficiency model RMSE, Bias, d and SB values were computed as specified in section 3.7. The values obtained were 0.314, 0.194, 0.974 and 0.073, respectively. (See detailed computations in Appendix III). The small values of these evaluation parameters between the predicted and measured values indicates a better model because it shows that there exist but a little deviation between the predicted and measured values. Fig 4.4 shows the graph of predicted versus measured values of shelling efficiency. A statistically significantly high coefficient of determination (r^2) of 0.937 was obtained with the regression equation of $y = 1.037x - 3.513$.

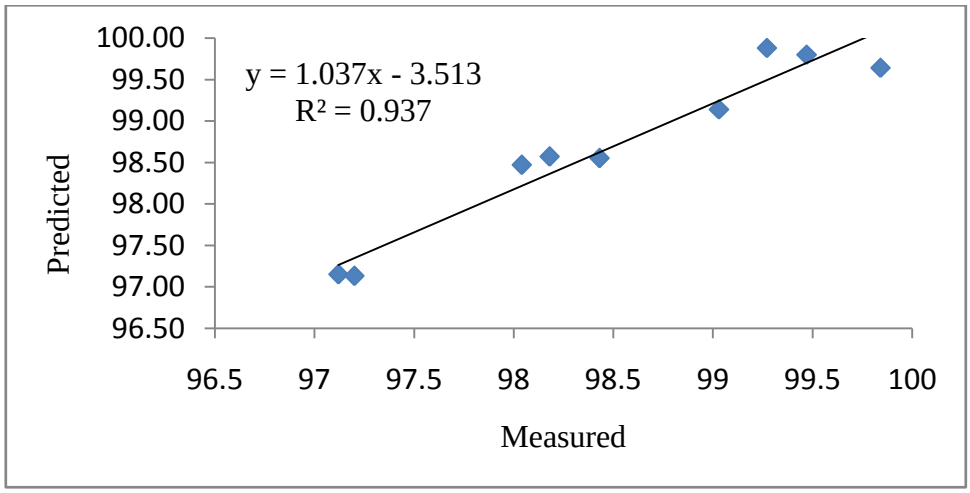

Fig. 4.4: Plot of Predicted against measured values of shelling efficiency

The computed values of t_b =2.072 and t_α= 0.038 (Appendix III) are less than the table value t_c = 2.365 even at 5 % level of significance. Hence the null hypothesis is upheld that the slope is not statistically different from 1.0 and the intercept is not statistically different from zero. This showed that there is no significant difference between the predicted and measured shelling efficiency values. Computed sensitivity values are shown in Table 4.16. From the absolute value (It is irrespective of the sign, the sign signifies the direction because of the derivative), it could be seen that concave clearance variable has the highest sensitivity in the shelling efficiency prediction model.

4.5 Grain Damage Model

From section 3.0, the following pi terms were determined

$\pi_1 = \lambda_D C$, $\pi_2 = \frac{\rho_g V C^2}{F_r}$ and $\pi_3 = \frac{C}{DM}$ Where the symbols take their established definitions. Plots of π_1 against π_2 holding π_3 constant and π_1 against π_3 holding π_2 constant were performed. The results are as shown figures 4.5 and 4.6. Additional supplementary equation relating π_1 with π_2 was generated by holding π_3 constant at different value from its magnitude in the original component equation (Fig 4.7)

From the figures, the following component equations were produced

$\pi_1 = 0.00020\ \pi_2^{0.948}$ (4.10)

$\pi_1 = 0.00174\ \pi_3^{0.783}$ (4.11)

$\pi_1 = 0.00021\ \pi_2^{0.942}$ (4.12)

Table 4.16: Sensitivity coefficient of the shelling efficiency model

Independent variable	Sensitivity coefficient	Contribution, %
Drum Speed (V)	0.01916	14.17
Concave clearance (C)	0.02690	19.89
Feed Rate (F_r)	-0.01916	14.17
Bulk Density (ρ_g)	0.01916	14.17
Drum Diametre (D)	-0.02543	18.80
Moisture Content(M)	-0.02543	18.80

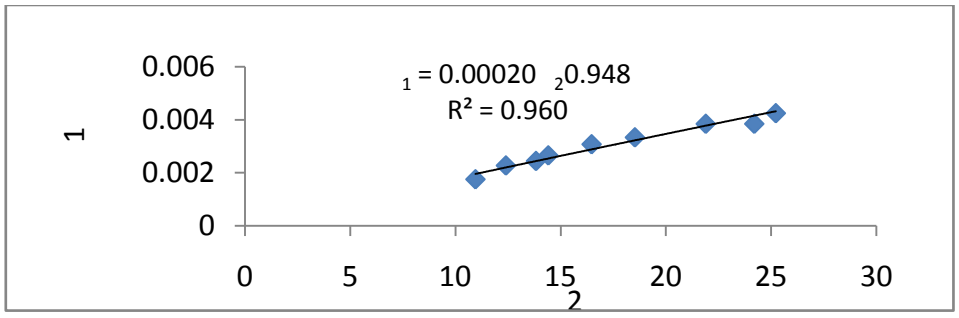

Fig 4.5: Plot of π_1 against π_2 for Damage

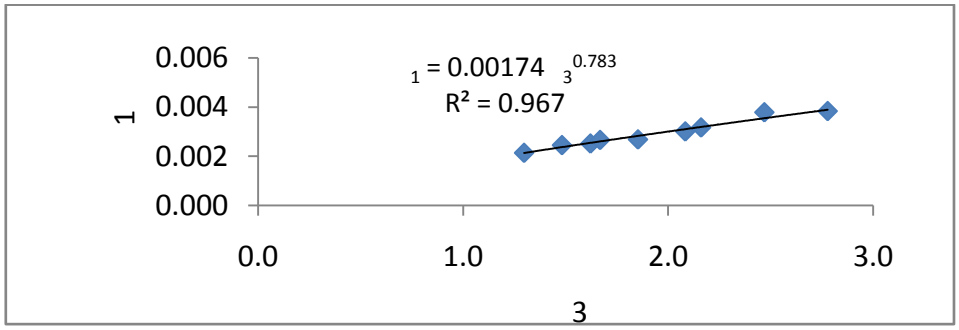

Fig 4.6 Plot of π_1 against π_3 for Damage

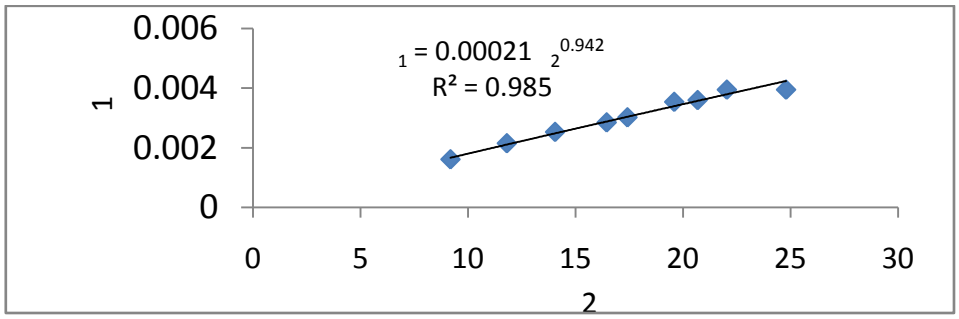

Fig 4.7 Plot of π_1 against π_2 for Damage (supplementary data)

From the analysis by Murphy (1950) as explained in chapter 2.0, for product validity (equation 2.47), then

$A\bar{\pi}_2{}^m$ = 0.00020 (17.54)$^{0.948}$ = 0.0030225 (4.13)

$C\bar{\pi}_2{}^m$ = 0.00021(17.33)$^{0.942}$ = 0.0030844 (4.14)

substituting, $$\frac{0.00020\ \pi_2{}^{0.948}}{0.0030225} = \frac{0.00021\ \pi_2{}^{0.942}}{00.0030844} \quad (4.15)$$

Or 6.16876E-07 $\pi_2{}^{0.948} = 6.3473\text{E-}07\ \pi_2{}^{0.942}$ (4.16)

Substituting any arbitrary value of π_2, say 17.0, the right hand side (9.15529E-06) is almost the same as the left hand side (9.0503 E-06). Hence this makes the combination of the component equations by multiplication valid. The prediction equation is thus formed by the product combination of the component equations divided by the constant (see equation 2.40). Substituting values and rearranging, (see detailed computation in Appendix III) the prediction equation for damage parameter is thus established:

$$\lambda_D = 1.15E-04\ C^{1.68}\left(\frac{\rho_g V}{F_r}\right)^{0.95}\left(\frac{1}{DM}\right)^{0.78} \quad (4.17)$$

From earlier literature review in section 2.6.1, it was established that at the end of the shelling length *l*, the shelling loss, say V_t, was given by equation 2.23. Similarly, the Damage percentage, η_D, becomes

η_D ==(1 - $e^{-\lambda_D l}$) x 100 % (4.18)

4.5.1 Damage model evaluation

In evaluation of the Damage model RMSE, Bias, d and SB values of 0.453, 0.121, 0.907 and 0.0144 were computed respectively as specified in section 3.7.

The small values of these evaluation parameters between the predicted and measured values indicates a better model because it shows that there exist but a little deviation between the predicted and measured values. Fig 4.8 shows the graph of predicted versus measured values of damage. A significantly high coefficient of determination (r^2) = 0.901 was obtained with the regression equation $y = 0.975x + 0.227$. The t-test shows that the computed values of t_b =2.064 and t_α= 0.140 (Appendix III) are less than the table value t_c = 2.365 even at 5 % level of significance. Hence the null hypothesis is upheld that the slope is not statistically different from 1.0 and the intercept is not statistically different from zero. This showed that there is no significant difference between the predicted and measured grain damage values. Computed sensitivity coefficient values are shown in table 4.17. From the absolute values (i.e. irrespective of the sign, the sign signifies the direction because of the derivative), it could be seen that the concave clearance was the least sensitive variable in the grain damage prediction model.

4.6 Grain Loss Model

Same variables affecting shelling were also considered to affect separation. The pi terms for Grain separation parameter β, similar to the shelling parameter were therefore determined as follows. From chapter three, the following pi terms were determined:

$\pi_1 = \beta C$, $\pi_2 = \frac{\rho_g V C^2}{F_r}$ and $\pi_3 = \frac{C}{DM}$; Where the symbols take their established definitions. Plots of π_1 against π_2 holding π_3 constant and π_1 against π_3 holding π_2 constant were performed.

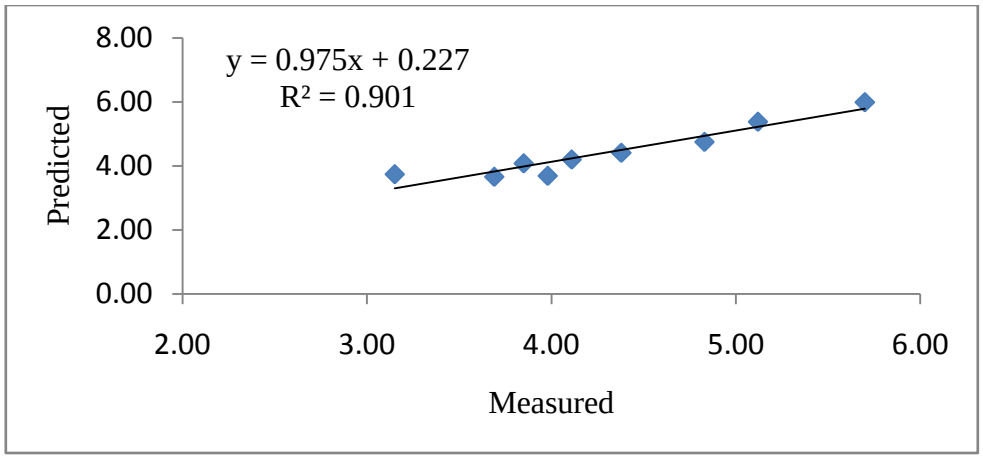

Fig. 4.8: Plot of Predicted against Measured values of grain damage

Table 4.17: Sensitivity coefficients of the Grain damage model

Independent variable	Sensitivity coefficient	Contribution, %
Drum Speed (V)	0.15960	21.24
Concave clearance (C)	0.01060	1.40
Feed Rate (F_r)	-0. 15960	21.24
Bulk Density (ρ_g)	0.15960	21.24
Drum Diametre (D)	-0.13104	17.44
Moisture Content(M)	-0.13104	17.44

The results are as shown in figures 4.9 and 4.10. Additional supplementary equation relating π_1 with π_2 was generated by holding π_3 constant at different value from its magnitude in the original component equation (Fig 4.11). From the figures, the following component equations were produced

$\pi_1 = 0.651\pi_2^{-0.48}$ (4.19)

$\pi_1 = 0.198\pi_3^{-0.33}$ (4.20)

$\pi_1 = 0.514\pi_2^{-0.40}$ (4.21)

From the analysis by Murphy (1950) as explained in chapter 2.0, for product validity (equation 2.47), then

$A\bar{\pi}_2^{\,m} = 0.651\ (18.75)^{-0.48} = 0.1594$ (4.22)

$C\bar{\pi}_2^{\,m} = 0.514(16.73)^{-0.40} = 0.1665$ (4.23)

substituting, $$\frac{0.651\ \pi_2^{-0.48}}{0.1594} = \frac{0.514\ \pi_2^{-0.40}}{0.1665} \quad (4.24)$$

$$0.108429\ \pi_2^{-0.48} = 0.081941\ \pi_2^{-0.40} \quad (4.25)$$

Substituting any arbitrary value of π_2, say 17.0, the right hand side (0.0264) is almost the same as the left hand side (0.0278). Hence this makes the combination of the component equations by multiplication valid. The prediction equation is formed by the product combination of the component equations divided by the constant (see equation 2.40).

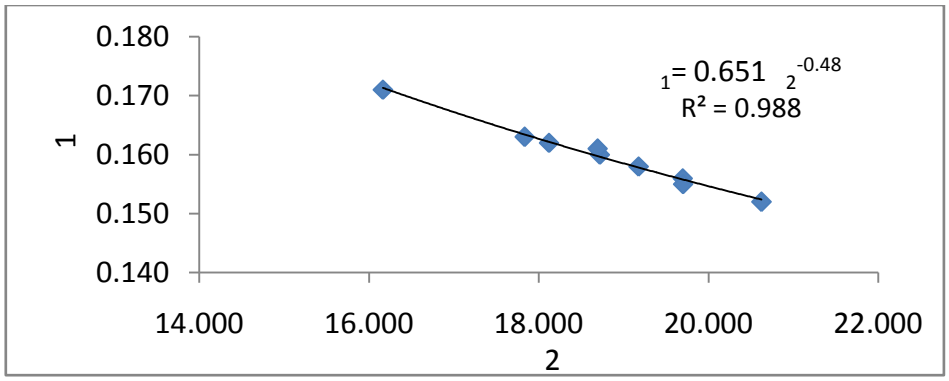

Fig 4.9 Plot of π_1 against π_2 for Grain loss

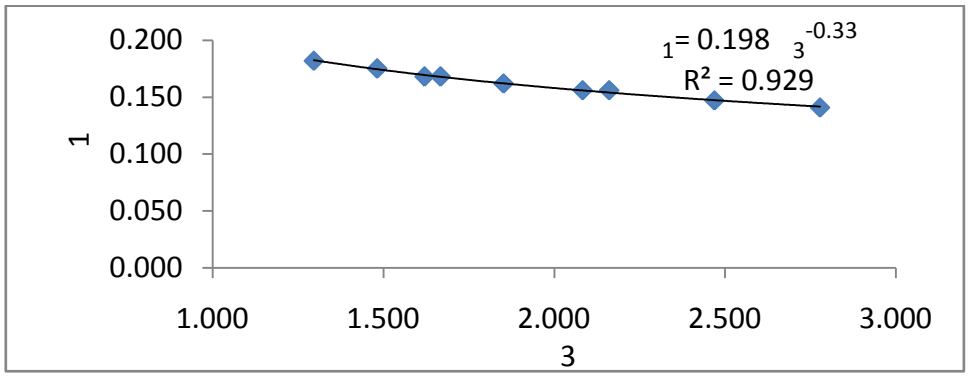

Fig 4.10 Plot of π_1 against π_3 for Grain loss

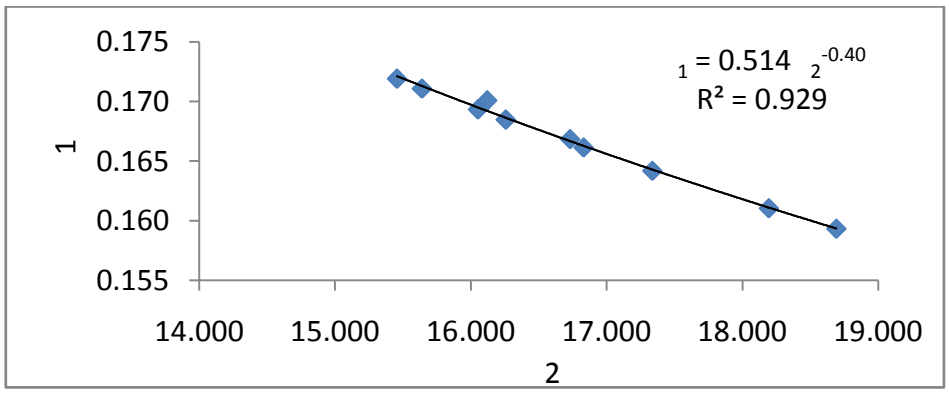

Fig 4.11 Plot of π_1 against π_2 for Grain loss (supplementary)

Substituting values and rearranging, (see detailed computation in Appendix III) the prediction equation for grain loss separation parameter is thus established:

$$\beta_S = 0.81 \left(\frac{1}{C}\right)^{2.29} \left(\frac{F_r}{\rho_g V}\right)^{0.48} (DM)^{0.33} \quad (4.26)$$

From earlier literature review in section 2.6.1, it was established that at the end of threshing space (*x*=*L*) the free grain becomes *separation loss V*s:

$$V_s = S_f(L) = \frac{\lambda_S}{\lambda_S - \beta_S}(e^{-\beta_S L} - e^{-\lambda_S L}) \quad (4.27)$$

λ_S and β_S are computed based on equations (4.8) and (4.26), respectively.

4.6.1 Grain loss model evaluation

In evaluation of the Grain loss model evaluation values were computed as specified in section 3.7. The values obtained for RMSE. Bias, d and SB are 1.462, -1.262, 0.629 and 1.587 respectively. The small values of these evaluation parameters between the predicted and measured values indicates a better model because it shows that there exist but a little deviation between the predicted and measured values. Fig 4.12 shows the graph of predicted versus measured values of grain loss. A significantly high coefficient of determination (r^2) = 0.733, was obtained with the regression equation$y = 1.048x + 1.919$. The t-test shows that the computed values of t_b =2.028 and t_α= 0.478 (Appendix III) are less than the table value t_c = 2.365 even at 5 % level of significance. Hence the null hypothesis is upheld that the slope is not statistically different from 1.0 and the intercept is not statistically different from zero. This showed that there is no significant difference between the predicted and measured grain loss values..

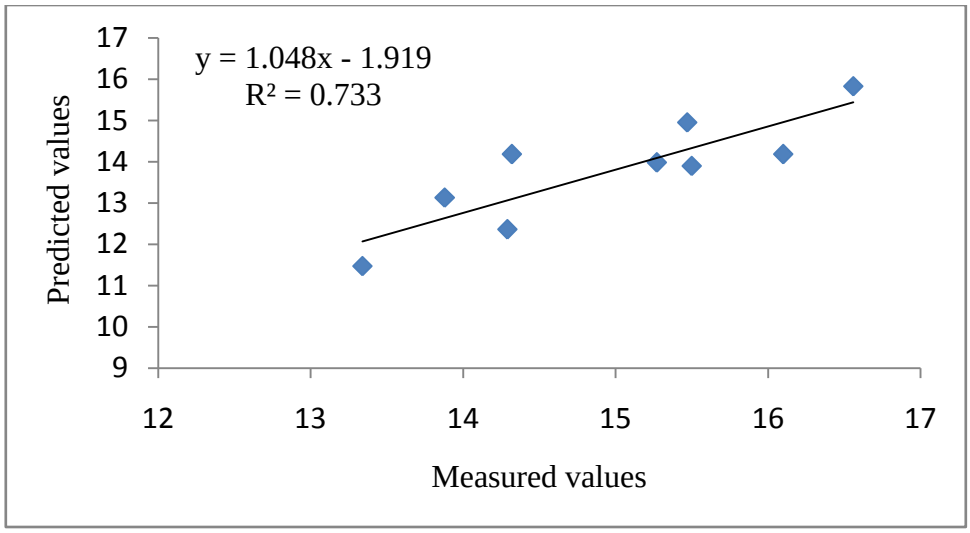

Fig. 4.12: Plot of Predicted against Measured values for grain loss

4.7 Optimization Results

With a population size of 100, a roulette selection function, adapt feasible mutation function, heuristic crossover function and vectorized objective function, the algorithm did not converge early. At 100^{th} generation, the algorithm was terminated. Table 4.18 represents output of the bounds for the input variables for the optimization process. The results of the best individual component variables (maize bulk density, feed rate, cylinder drum diameter, cylinder speed, cylinder-concave clearance, grain moisture content (wet basis) and shelling length) obtained for the two evaluation functions (equal and selective weights) are shown in table 4.19. T-test showed that the differences between the mean values for the two evaluation functions used are not statistically significant. Using selective weight evaluation function was not to emphasize the importance of one output performance parameter than another but to ensure that the search of the optimal solution is directed towards narrow regions of the solution space. The set of best performance parameter which were obtained are:

Shelling Efficiency= 99.18 %

Grain damage = 4.23 %

Grain loss = 6.31 %

Table 4.18: Bounds for Variables

Variable limits	Variables ρ	f	d	s	c	m	l
Lower	600	0.60	0.17	7.0	0.030	0.09	0.50
Upper	900	0.90	0.20	9.0	0.045	0.13	0.95

Table 4.19: Best Individual components

variable	ρ, kgm^{-3}	f, kgs^{-1}	d, m	s, ms^{-1}	c, m	m, %	l, m
GA1	677.67	0.605	0.180	8.49	0.042	0.108	0.797
GA2	641.86	0.617	0.179	8.70	0.040	0.104	0.775

CHAPTER FIVE

5.0 SUMMARY, CONCLUSION AND RECOMMENDA

5.1 Summary

This study was conducted in order to optimize the performance of the maize dehusker sheller developed at the Institute for Agricultural Research (IAR), Ahmadu Bello University, Zaria. To facilitate this, a study on some physical properties of ACR, QPM and TZPB maize varieties in relation to moisture content was conducted. Also three mathematical models for shelling, grain damage and loss were developed based on dimensional analysis. The models developed and validated were both enhanced through performance evaluation experiments conducted with speed, feed rate, moisture content and cylinder concave clearance as variables each at three levels in a completely randomized block design. The effects of moisture content and maize grain variety were highly significant for all the parameters considered. TZPB variety has the highest mean values of length, width thickness and one thousand grain mass of 1.320 1.102, 0.492 and 375.36 ± 9.15 respectively at 15 % moisture content (wb). The least was the ACR variety with 1.184, 1.029 0.0450 and 291.79 ± 9.04 respectively. ACR has the highest mean values of bulk density 876.40 ± 34.05 at 9 % Moisture content (wb). The analysis of variance shows that all the variables have significant effect on the performance indices. The model developed mean results for Output, shelling, cleaning, damage and loss were 609.55 kg/h, 98.06 %, 87.12%, 4.25 % and 14.08 % respectively. Validated mean results for those indices were 578.26 kg/h, 98.18 %, 94.44 %, 3.97 % and 14.75 %, respectively. The different indices of model evaluation namely, bias, root mean square error, index of agreement, square bias and coefficient of determination, between the predicted values and

the measured values were: 0.314, 0.194, 0.974, 0.073 and 0.937, respectively for shelling; 0.453, 0.121, 0.907, 0.0144 and 0.901, respectively for grain damage and 1.462, 1.262. 0.629, 1.587 and 0.733, respectively, for grain loss.

Optimization based on formulation of a multi-objective genetic algorithm in MATLAB R2008a toolbox was used in this study. Seven (7) functional parameters (variables) under upper and lower constraints and three (3) performance criteria objectives were considered in the decision process in search of optimal solution. The optimal values of the variables were 641.86 kgm^{-3}, 0.617 kgs^{-1}, 0.179 m, 8.70 ms^{-1}, 0.04 m, 10.4 %, and 0.775 m for maize bulk density, feed rate, cylinder drum diameter, cylinder speed, cylinder-concave clearance, grain moisture content (wet basis) and shelling length, respectively. The optimum performance parameters obtained were 99.18 %, 4.23 % and 6.31 % for shelling efficiency, grain damage and grain loss, respectively. Thus, parameters for an optimized sheller with maximized shelling and minimized damages and losses have been established.

5.2 Conclusion.

1. Some Physical properties (length, width, thickness, bulk density and a thousand grain mass) of ACR, QPM and TZPB maize varieties in relation to moisture content (at three levels, 9, 12 and 15 % wet basis) were determined. Moisture content had significant effects on the physical properties of the maize varieties. There are significant differences in physical properties for the different maize varieties considered.
2. Two sets of Performance evaluation tests of the existing IAR maize dehusker sheller were conducted one for models developed and the other for validation of

the developed models. All the variable independent factors (cylinder speed, crop feed rate, cylinder-concave clearance and crop moisture content each at three levels) have significant effects on the dependent performance indices (shelling efficiency, cleaning efficiency, output capacity, grain damage and scatter loss) for both sets of experiment.

3. Shelling efficiency, grain damage and grain scatter loss prediction models were developed and validated. There was good agreement between the prediction models and the experimental results.
4. The performance of the sheller was optimized based on maximum shelling efficiency and minimum grain damage and minimum scatter loss.

5.3 Recommendations

1. Further work on the determination of other properties such as crushing strength, hardness and porosity for the studied maize varieties that were not conducted in this work, should be done.
2. Power operated maize dehusker shellers should use operational variables of feed rate, speed, crop moisture content, machine factors which include cylinder diameter, cylinder concave clearance and threshing length as specified in this work so as to obtain maximum shelling efficiency and minimal grain damage and loss.
3. There are other machine and crop factors such as concave size, shape, holes configuration and cob-grain ratio that were not incorporated in this work. There is need for further studies to incorporate these factors to enhance the work.

4. Some aerodynamic factors such as fan speed, Drag coefficient and grain terminal velocity were not considered due to scope considerations in the modeling process. Further study is recommended to develop a cleaning efficiency model which could incorporate those factors. With cleaning as a factor to be maximized, the suggested work would improve the optimization process.

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APPENDIX I

Table AI-1: Field Layout and Randomization

REPLICATION I								
S3F1C1M1	S1F2C2M3	S2F2C3M2	S1F3C3M3	S1F1C1M1	S3F3C1M3	S2F1C1M2	S1F2C1M1	S1F1C2M2
S3F2C1M1	S2F1C3M3	S2F3C3M2	S2F2C2M3	S3F1C2M1	S1F2C3M3	S3F3C3M2	S2F3C1M1	S2F2C2M2
S1F1C2M1	S3F3C2M3	S3F2C3M2	S1F1C3M3	S2F3C2M1	S2F2C3M3	S1F1C1M2	S2F3C3M1	S1F3C3M2
S2F2C1M1	S1F3C1M3	S2F1C2M2	S3F2C2M3	S2F1C1M1	S1F3C2M3	S3F1C3M2	S1F3C2M1	S2F3C1M2
S3F3C3M1	S3F1C3M3	S1F2C1M2	S2F2C1M3	S1F3C1M1	S2F1C2M3	S2F3C2M2	S2F2C3M1	S1F2C3M2
S3F2C2M1	S2F1C1M3	S1F3C2M2	S3F3C3M3	S3F1C3M1	S1F2C1M3	S1F2C2M2	S3F3C1M1	S3F2C2M2
S1F1C3M1	S2F3C2M3	S2F1C3M2	S1F1C2M3	S3F3C2M1	S3F2C3M3	S3F2C1M2	S1F2C3M1	S3F1C2M2
S2F2C2M1	S3F1C2M3	S1F1C3M2	S3F2C1M3	S2F1C3M1	S2F3C3M3	S2F2C1M2	S3F2C3M1	S3F1C1M2
S1F3C3M1	S1F1C1M3	S3F3C1M2	S3F1C1M3	S1F2C2M1	S2F3C1M3	S1F3C1M2	S2F1C2M1	S3F3C2M2
REPLICATION II								
S2F3C1M3	S2F1C1M2	S2F1C2M1	S1F1C2M2	S1F2C2M1	S1F3C3M3	S3F1C1M1	S2F2C3M2	S1F2C2M3
S2F3C3M3	S3F3C3M2	S3F2C3M1	S2F2C2M2	S2F1C3M1	S2F2C2M3	S3F2C1M1	S2F3C3M2	S2F1C3M3
S3F2C3M3	S1F1C1M2	S1F2C3M1	S1F3C3M2	S3F3C2M1	S1F1C3M3	S1F1C2M1	S3F2C3M2	S3F3C2M3
S1F2C1M3	S3F1C3M2	S3F3C1M1	S2F3C1M2	S3F1C3M1	S3F2C2M3	S2F2C1M1	S2F1C2M2	S1F3C1M3
S2F1C2M3	S2F3C2M2	S2F2C3M1	S1F2C3M2	S1F3C1M1	S2F2C1M3	S3F3C3M1	S1F2C1M2	S3F1C3M3
S1F3C2M3	S1F2C2M2	S1F3C2M1	S3F2C2M2	S2F1C1M1	S3F3C3M3	S3F2C2M1	S1F3C2M2	S2F1C1M3
S2F2C3M3	S3F2C1M2	S2F3C3M1	S3F1C2M2	S2F3C2M1	S1F1C2M3	S1F1C3M1	S2F1C3M2	S2F3C2M3
S1F2C3M3	S2F2C1M2	S2F3C1M1	S3F1C1M2	S3F1C2M1	S3F2C1M3	S2F2C2M1	S1F1C3M2	S3F1C2M3
S3F3C1M3	S1F3C1M2	S1F2C1M1	S3F3C2M2	S1F1C1M1	S3F1C1M3	S1F3C3M1	S3F3C1M2	S1F1C1M3
REPLICATION III								
S2F2C3M2	S1F2C2M1	S1F2C2M3	S3F1C1M1	S2F3C1M3	S1F1C2M2	S1F3C3M3	S2F1C2M1	S2F1C1M2
S2F3C3M2	S2F1C3M1	S2F1C3M3	S3F2C1M1	S2F3C3M3	S2F2C2M2	S2F2C2M3	S3F2C3M1	S3F3C3M2
S3F2C3M2	S3F3C2M1	S3F3C2M3	S1F1C2M1	S3F2C3M3	S1F3C3M2	S1F1C3M3	S1F2C3M1	S1F1C1M2
S2F1C2M2	S3F1C3M1	S1F3C1M3	S2F2C1M1	S1F2C1M3	S2F3C1M2	S3F2C2M3	S3F3C1M1	S3F1C3M2

S1F2C1M2	S1F3C1M1	S3F1C3M3	S3F3C3M1	S2F1C2M3	S1F2C3M2	S2F2C1M3	S2F2C3M1	S2F3C2M2
S1F3C2M2	S2F1C1M1	S2F1C1M3	S3F2C2M1	S1F3C2M3	S3F2C2M2	S3F3C3M3	S1F3C2M1	S1F2C2M2
S2F1C3M2	S2F3C2M1	S2F3C2M3	S1F1C3M1	S2F2C3M3	S3F1C2M2	S1F1C2M3	S2F3C3M1	S3F2C1M2
S1F1C3M2	S3F1C2M1	S3F1C2M3	S2F2C2M1	S1F2C3M3	S3F1C1M2	S3F2C1M3	S2F3C1M1	S2F2C1M2
S3F3C1M2	S1F1C1M1	S1F1C1M3	S1F3C3M1	S3F3C1M3	S3F3C2M2	S3F1C1M3	S1F2C1M1	S1F3C1M2

APPENDIX I (contd)

Table AI-2: ANOVA for a 3^4 Factorial Experiment in a Randomized Complete Block Design

Source	**Degrees of Freedom,**	**DF**	**SS**	**MS**	**F**
Replication, R	r-1	2			
Speed, S	s-1	2			
Feed rate, F	f-1	2			
Concave clearance, C	c-1	2			
Moisture content, M	m-1	2			
S*F	(s-1)(f-1)	4			
S*C	(s-1)(c-1)	4			
S*M	(s-1)(m-1)	4			
F*C	(f-1)(c-1)	4			
F*M	(f-1)(m-1)	4			
C*M	(c-1)(m-1)	4			
S*F*C	(s-1)(f-1)(c-1)	8			
S*F*M	(s-1)(f-1)(m-1)	8			
S*C*M	(s-1)(c-1)(m-1)	8			
F*C*M	(f-1)(c-1)(m-1)	8			
S*F*C*M	(s-1)(f-1)(c-1)(m-1)	16			
Error	(sfcm-1)(r-1)	160			
Total	rsfcm-1	242			

Appendix I (contd)

Model Development Data

Table AI-3: Sheller Performance Parametres at Different Variable Combinations (9 % MC)

REP	OBS	SPD	FDR	CLR	MC	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	mm	%, wb	Kg/h	Eff, %	Eff, %	%	%
1	1	750	30	35	9	520.89	98.44	87.44	5.10	13.80
1	2	750	40	35	9	680.54	98.16	87.14	4.05	12.95
1	3	750	50	35	9	726.03	97.90	86.83	2.70	12.35
1	4	850	30	35	9	611.70	99.13	91.24	6.19	14.58
1	5	850	40	35	9	730.12	99.81	90.07	5.30	14.05
1	6	850	50	35	9	812.20	98.45	89.20	5.05	13.82
1	7	950	30	35	9	845.10	99.81	95.18	7.03	15.45
1	8	950	40	35	9	880.37	99.46	94.07	6.35	14.98
1	9	950	50	35	9	909.06	99.07	93.40	5.28	14.35
1	10	750	30	40	9	490.40	98.09	86.10	4.90	14.20
1	11	750	40	40	9	651.68	97.88	85.84	3.82	13.80
1	12	750	50	40	9	680.52	97.58	85.55	2.54	13.29
1	13	850	30	40	9	555.84	98.80	90.30	5.92	14.94
1	14	850	40	40	9	692.93	98.46	88.75	5.03	14.60
1	15	850	50	40	9	758.75	98.15	87.87	4.62	14.30
1	16	950	30	40	9	797.25	99.51	97.44	6.70	15.82
1	17	950	40	40	9	829.45	99.19	94.85	6.10	15.26
1	18	950	50	40	9	847.60	98.79	93.96	5.18	14.95
1	19	750	30	45	9	507.89	97.88	84.82	4.58	14.46
1	20	750	40	45	9	600.65	97.57	84.45	3.65	14.10
1	21	750	50	45	9	613.86	97.20	84.20	2.30	13.65
1	22	850	30	45	9	548.92	98.60	88.85	5.60	15.62
1	23	850	40	45	9	700.09	98.22	88.30	4.80	15.24

1	24	850	50	45	9	700.87	97.96	87.77	4.30	14.70
1	25	950	30	45	9	720.87	99.33	93.77	6.55	16.05
1	26	950	40	45	9	778.38	98.99	92.38	5.82	15.77
1	27	950	50	45	9	814.48	98.59	91.75	4.95	15.30

APPENDIX I (contd)

Model Development Data

Table AI-4: Sheller Performance Parametres at Different Variable Combinations (9 % MC)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	Mm	wb	Kg/h	Eff, %	Eff, %	%	%
2	1	750	30	35	9	524.91	98.40	87.46	5.15	13.83
2	2	750	40	35	9	708.59	98.15	87.16	4.10	12.97
2	3	750	50	35	9	734.61	97.93	86.86	2.68	12.30
2	4	850	30	35	9	610.10	99.14	91.26	6.20	14.60
2	5	850	40	35	9	736.09	99.79	90.05	5.32	13.98
2	6	850	50	35	9	806.80	98.48	89.22	5.08	13.85
2	7	950	30	35	9	850.29	99.79	95.16	7.00	15.46
2	8	950	40	35	9	892.22	99.44	94.06	6.38	15.02
2	9	950	50	35	9	917.08	99.06	93.42	5.30	14.33
2	10	750	30	40	9	505.17	98.06	86.11	4.85	14.20
2	11	750	40	40	9	651.91	97.89	85.87	3.86	13.85
2	12	750	50	40	9	672.99	97.56	85.58	2.57	13.32
2	13	850	30	40	9	555.90	98.80	90.29	5.89	14.96
2	14	850	40	40	9	707.54	98.45	88.74	5.06	14.55
2	15	850	50	40	9	783.65	98.16	87.9	4.60	14.25
2	16	950	30	40	9	789.26	99.52	97.47	6.70	15.80
2	17	950	40	40	9	830.80	99.18	94.82	6.18	15.28
2	18	950	50	40	9	877.92	98.78	93.95	5.20	14.92
2	19	750	30	45	9	408.95	97.88	84.85	4.60	14.44
2	20	750	40	45	9	611.60	97.59	84.46	3.67	14.06
2	21	750	50	45	9	645.5	97.19	84.19	2.35	13.68
2	22	850	30	45	9	504.63	98.61	88.83	5.58	15.65

2	23	850	40	45	9	574.24	98.26	88.32	4.86	15.20
2	24	850	50	45	9	733.63	97.92	87.74	4.33	14.75
2	25	950	30	45	9	781.23	99.32	93.76	6.54	16.10
2	26	950	40	45	9	798.20	99.00	92.36	5.85	15.75
2	27	950	50	45	9	817.74	98.6	91.79	4.9	15.28

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Model Development Data

Table AI-5: Sheller Performance Parametres at Different Variable Combinations (9 % MC)

REP	OBS	SPD rpm	FDR Kg/min	CLR Mm	MC %, wb	Output, Kg/h	Shelling Eff, %	Cleaning Eff, %	Damage %	SCLoss %
3	1	750	30	35	9	530.40	98.39	87.39	5.17	13.92
3	2	750	40	35	9	700.22	98.17	87.12	4.09	12.96
3	3	750	50	35	9	725.76	97.90	86.86	2.75	12.28
3	4	850	30	35	9	609.70	99.18	91.25	6.24	14.65
3	5	850	40	35	9	709.69	96.80	90.09	5.34	14.00
3	6	850	50	35	9	820.30	98.48	89.27	5.11	13.85
3	7	950	30	35	9	850.05	99.80	95.2	6.97	15.47
3	8	950	40	35	9	873.56	99.45	94.11	6.38	15.00
3	9	950	50	35	9	920.72	99.08	93.38	5.35	14.37
3	10	750	30	40	9	485.83	98.09	86.15	4.83	14.14
3	11	750	40	40	9	660.15	97.90	85.81	3.90	13.81
3	12	750	50	40	9	690.87	97.57	85.52	2.54	13.38
3	13	850	30	40	9	573.24	98.83	90.31	5.89	14.95
3	14	850	40	40	9	688.40	98.44	88.67	5.06	14.56
3	15	850	50	40	9	750.50	98.17	87.9	4.67	14.35
3	16	950	30	40	9	818.95	99.53	97.44	6.76	15.87
3	17	950	40	40	9	840.46	99.20	94.88	6.17	15.27
3	18	950	50	40	9	850.88	98.77	93.97	5.16	14.95
3	19	750	30	45	9	460.85	97.88	84.82	4.59	14.48
3	20	750	40	45	9	594.38	97.58	84.44	3.69	14.08
3	21	750	50	45	9	620.94	97.21	84.15	2.34	13.68

3	22	850	30	45	9	530.33	98.62	88.87	5.65	15.65
3	23	850	40	45	9	678.76	98.27	88.34	4.89	15.22
3	24	850	50	45	9	709.36	98.00	87.74	4.33	14.77
3	25	950	30	45	9	735.00	99.31	93.75	6.56	16.09
3	26	950	40	45	9	773.92	98.98	92.4	5.85	15.70
3	27	950	50	45	9	789.68	98.55	91.8	4.91	15.32

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Model Development Data

Table AI -6: Sheller Performance Parametres at Different Variable Combinations (12 % MC)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	mm	wb	Kg/h	Eff, %	Eff, %	%	%
1	1	750	30	35	12	475.85	98.03	83.98	3.96	13.28
1	2	750	40	35	12	534.08	97.76	82.83	3.63	12.52
1	3	750	50	35	12	600.55	97.47	81.96	3.09	12.09
1	4	850	30	35	12	522.60	98.63	90.63	4.78	14.25
1	5	850	40	35	12	673.80	98.31	88.82	4.40	13.78
1	6	850	50	35	12	708.50	98.02	88.10	4.13	13.28
1	7	950	30	35	12	613.50	99.34	90.42	5.62	14.66
1	8	950	40	35	12	745.65	99.07	94.02	5.25	13.50
1	9	950	50	35	12	760.85	98.70	92.76	4.82	13.02
1	10	750	30	40	12	448.40	97.82	82.40	3.77	14.63
1	11	750	40	40	12	499.54	97.58	81.38	3.45	14.20
1	12	750	50	40	12	570.68	97.25	81.02	2.35	13.73
1	13	850	30	40	12	490.85	98.33	89.50	4.36	15.50
1	14	850	40	40	12	639.72	98.07	88.22	4.16	15.15
1	15	850	50	40	12	667.74	97.81	87.14	3.70	14.70
1	16	950	30	40	12	587.52	99.05	94.47	5.13	17.08
1	17	950	40	40	12	702.54	98.81	93.93	4.75	16.47
1	18	950	50	40	12	730.45	98.40	90.47	4.64	15.45
1	19	750	30	45	12	432.80	97.33	81.45	3.66	14.03
1	20	750	40	45	12	468.05	97.05	80.24	3.09	13.75

1	21	750	50	45	12	535.19	96.80	79.81	2.13	13.30
1	22	850	30	45	12	455.95	97.83	87.15	4.21	15.24
1	23	850	40	45	12	610.82	97.60	86.60	3.82	14.85
1	24	850	50	45	12	630.41	97.30	85.92	3.50	14.20
1	25	950	30	45	12	556.05	98.67	92.97	4.82	15.00
1	26	950	40	45	12	660.08	98.35	91.75	4.60	14.66
1	27	950	50	45	12	676.94	97.91	90.95	4.27	14.07

APPENDIX I (contd)

Model Development Data

Table AI-7: Sheller Performance Parametres at Different Variable Combinations (12 % MC)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	mm	wb	Kg/h	Eff, %	Eff, %	%	%
2	1	750	30	35	12	483.60	98.02	83.94	3.95	13.31
2	2	750	40	35	12	530.00	97.75	82.86	3.66	12.48
2	3	750	50	35	12	598.75	97.45	81.95	3.09	12.11
2	4	850	30	35	12	525.08	98.66	90.62	4.80	14.26
2	5	850	40	35	12	671.75	98.33	88.80	4.43	13.74
2	6	850	50	35	12	702.08	98.03	88.12	4.16	13.25
2	7	950	30	35	12	615.00	99.31	90.40	5.59	14.68
2	8	950	40	35	12	739.05	99.08	94.04	5.24	13.54
2	9	950	50	35	12	765.55	98.67	92.73	4.85	12.98
2	10	750	30	40	12	457.00	97.84	82.36	3.75	14.64
2	11	750	40	40	12	494.75	97.57	81.32	3.46	14.18
2	12	750	50	40	12	567.85	97.28	81.04	2.30	13.70
2	13	850	30	40	12	493.15	98.31	89.52	4.41	15.48
2	14	850	40	40	12	634.95	98.06	88.25	4.12	15.10
2	15	850	50	40	12	658.90	97.82	87.15	3.75	14.67
2	16	950	30	40	12	579.89	99.07	94.48	5.15	17.11
2	17	950	40	40	12	715.00	98.80	93.95	4.71	16.50

2	18	950	50	40	12	728.99	98.41	90.45	4.67	15.48
2	19	750	30	45	12	426.78	97.35	81.42	3.68	14.01
2	20	750	40	45	12	468.95	97.06	80.19	3.10	13.74
2	21	750	50	45	12	528.99	96.77	79.79	2.15	13.25
2	22	850	30	45	12	461.74	97.82	87.15	4.15	15.20
2	23	850	40	45	12	605.66	97.61	86.62	3.85	14.82
2	24	850	50	45	12	625.65	97.31	85.89	3.45	14.19
2	25	950	30	45	12	548.96	98.68	92.95	4.85	15.02
2	26	950	40	45	12	658.73	98.34	91.77	4.55	14.65
2	27	950	50	45	12	682.87	97.93	90.94	4.35	14.12

APPENDIX I (contd)

Model Development Data

Table AI-8:Sheller Performance Parametres at Different Variable Combinations (12% MC)

REP	OBS	SPD	FDR	CLRM	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	m	wb	Kg/h	Eff, %	Eff, %	%	%
3	1	750	30	35	12	482.05	98.07	83.93	4.00	13.31
3	2	750	40	35	12	523.67	97.77	82.86	3.66	12.50
3	3	750	50	35	12	608.50	97.46	81.91	3.06	12.10
3	4	850	30	35	12	514.42	98.66	90.55	4.79	14.30
3	5	850	40	35	12	666.01	98.32	88.78	4.40	13.73
3	6	850	50	35	12	706.22	98.01	88.14	4.16	13.31
3	7	950	30	35	12	621.72	99.37	90.44	5.59	14.61
3	8	950	40	35	12	737.85	99.09	93.97	5.29	13.52
3	9	950	50	35	12	774.75	98.73	92.76	4.85	13.00
3	10	750	30	40	12	449.58	97.83	82.38	3.73	14.59
3	11	750	40	40	12	498.21	97.56	81.38	3.47	14.19
3	12	750	50	40	12	575.28	97.28	81.00	2.31	13.76
3	13	850	30	40	12	489.03	98.29	89.45	4.37	15.52
3	14	850	40	40	12	636.33	98.08	88.28	4.14	15.11
3	15	850	50	40	12	673.88	97.83	87.16	3.74	14.70
3	16	950	30	40	12	590.29	99.03	94.43	5.17	17.08
3	17	950	40	40	12	697.97	98.82	93.97	4.73	16.47
3	18	950	50	40	12	724.35	98.42	90.49	4.67	15.48

3	19	750	30	45	12	420.85	97.34	81.45	3.67	14.02
3	20	750	40	45	12	473.42	97.04	80.23	3.14	13.73
3	21	750	50	45	12	526.12	96.77	79.80	2.14	13.29
3	22	850	30	45	12	459.61	97.84	87.12	4.18	15.22
3	23	850	40	45	12	598.97	97.59	86.58	3.85	14.82
3	24	850	50	45	12	628.54	97.29	85.89	3.46	14.15
3	25	950	30	45	12	547.24	98.69	92.96	4.85	15.04
3	26	950	40	45	12	669.77	98.36	91.76	4.56	14.61
3	27	950	50	45	12	681.99	97.92	90.99	4.28	14.11

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Model Development Data

Table AI-9: Sheller Performance Parametres at Different Variable Combinations (15 % MC)

REP	OBS	FDR	CLR	MC %,	Output	Shelling	Cleaning	Damage	SCLoss
		Kg/min	mm	wb	Kg/h	Eff, %	Eff, %	%	%
1	1	30	35	15	442.50	97.58	79.95	3.73	12.72
1	2	40	35	15	482.25	97.31	78.80	3.27	12.20
1	3	50	35	15	555.00	97.00	78.90	2.98	11.82
1	4	30	35	15	459.05	98.14	86.78	4.38	13.60
1	5	40	35	15	584.90	97.86	85.52	4.02	13.15
1	6	50	35	15	650.27	97.56	84.45	3.75	12.85
1	7	30	35	15	575.90	98.92	93.24	4.78	13.97
1	8	40	35	15	686.70	98.58	91.60	4.41	13.25
1	9	50	35	15	745.00	98.14	90.24	4.07	12.72
1	10	30	40	15	390.35	97.34	78.75	3.21	13.09
1	11	40	40	15	442.80	97.09	77.20	2.97	12.83
1	12	50	40	15	500.78	96.76	77.28	3.12	12.58
1	13	30	40	15	412.05	97.93	85.50	4.15	13.88
1	14	40	40	15	559.35	97.56	84.25	3.83	13.45
1	15	50	40	15	595.85	97.34	82.60	3.55	13.11
1	16	30	40	15	550.92	98.65	91.63	4.36	14.35
1	17	40	40	15	615.80	98.32	90.43	4.08	14.00
1	18	50	40	15	660.05	97.91	89.76	3.90	13.75

1	19	30	45	15	370.87	96.94	77.55	3.21	13.86
1	20	40	45	15	425.60	96.60	76.90	2.87	13.30
1	21	50	45	15	475.88	96.29	76.03	2.05	13.00
1	22	30	45	15	400.54	97.56	84.15	4.00	14.21
1	23	40	45	15	531.72	97.29	83.73	3.70	13.84
1	24	50	45	15	567.02	96.91	82.72	3.37	13.55
1	25	30	45	15	520.68	98.30	90.24	4.22	14.80
1	26	40	45	15	600.10	97.89	89.20	3.87	14.30
1	27	50	45	15	620.50	97.49	88.67	3.63	13.93

APPENDIX I (contd)

Model Development Data

Table AI - 10: Sheller Performance Parametres at Different Variable Combinations (15 % MC)

REP	OBS	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		Kg/min	mm	wb	Kg/h	Eff, %	Eff, %	%	%
2	1	30	35	15	448.15	97.58	79.93	3.68	12.67
2	2	40	35	15	483.44	97.34	78.78	3.32	12.25
2	3	50	35	15	558.85	97.03	78.88	3.00	11.85
2	4	30	35	15	460.45	98.13	86.82	4.32	13.57
2	5	40	35	15	590.02	98.88	88.49	4.04	13.10
2	6	50	35	15	641.75	97.57	84.49	3.72	12.82
2	7	30	35	15	570.58	98.93	93.27	4.74	14.02
2	8	40	35	15	679.85	98.57	91.55	4.38	13.30
2	9	50	35	15	738.67	98.17	90.26	4.05	12.69
2	10	30	40	15	384.76	97.35	78.77	3.17	13.05
2	11	40	40	15	443.54	97.04	77.15	3.00	12.78
2	12	50	40	15	490.55	96.76	77.30	3.09	12.55
2	13	30	40	15	421.15	97.90	85.48	4.17	13.86
2	14	40	40	15	560.00	97.58	84.24	3.85	13.42
2	15	50	40	15	609.56	97.30	82.57	3.57	13.12
2	16	30	40	15	538.73	98.66	91.65	4.40	14.30
2	17	40	40	15	621.68	98.30	90.42	4.05	14.02

2	18	50	40	15	648.75	97.92	89.76	3.85	13.70
2	19	30	45	15	355.72	96.96	77.58	3.18	13.80
2	20	40	45	15	412.97	96.62	79.92	2.82	13.28
2	21	50	45	15	469.95	96.30	76.10	2.00	12.99
2	22	30	45	15	405.08	97.59	84.17	4.03	14.15
2	23	40	45	15	520.65	97.27	83.74	3.68	13.79
2	24	50	45	15	564.45	96.89	82.73	3.42	13.48
2	25	30	45	15	529.05	98.31	90.26	4.27	14.75
2	26	40	45	15	595.76	97.90	89.24	3.84	14.25
2	27	50	45	15	630.44	97.52	88.70	3.58	13.88

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Model Development Data

Table AI -11: Sheller Performance Parametres at Different Variable Combinations (15 % MC)

REP	OBS	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		Kg/min	mm	wb	Kg/h	Eff, %	Eff, %	%	%
3	1	30	35	15	447.80	97.61	79.94	3.69	12.71
3	2	40	35	15	474.55	97.34	78.79	3.31	12.30
3	3	50	35	15	556.55	97.03	78.83	3.02	11.82
3	4	30	35	15	455.40	98.15	86.80	4.35	13.60
3	5	40	35	15	581.88	96.87	82.49	4.09	13.11
3	6	50	35	15	643.46	97.55	84.47	3.72	12.85
3	7	30	35	15	576.90	98.91	93.24	4.76	14.01
3	8	40	35	15	699.85	98.59	91.56	4.41	13.29
3	9	50	35	15	736.78	98.17	90.25	4.03	12.69
3	10	30	40	15	382.71	97.33	78.73	3.19	13.07
3	11	40	40	15	436.06	97.11	77.16	2.97	12.79
3	12	50	40	15	516.77	96.82	77.32	3.09	12.55
3	13	30	40	15	418.88	97.93	85.52	4.10	13.84
3	14	40	40	15	543.25	97.60	84.29	3.84	13.39
3	15	50	40	15	595.04	97.32	82.57	3.59	13.07
3	16	30	40	15	532.15	98.64	91.58	4.38	14.34

3	17	40	40	15	623.72	98.34	90.44	4.08	13.98
3	18	50	40	15	656.62	97.87	89.73	3.83	13.71
3	19	30	45	15	385.21	96.95	77.55	3.21	13.86
3	20	40	45	15	430.43	96.58	73.94	2.86	13.32
3	21	50	45	15	471.07	96.28	76.11	2.04	13.04
3	22	30	45	15	385.74	97.59	84.16	4.00	14.18
3	23	40	45	15	523.89	97.31	83.78	3.69	13.83
3	24	50	45	15	549.73	96.90	82.68	3.41	13.47
3	25	30	45	15	519.72	98.29	90.25	4.29	14.79
3	26	40	45	15	576.54	97.91	89.25	3.84	14.23
3	27	50	45	15	626.16	97.55	88.70	3.59	13.89

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Model Validation Data

Table AI -12: Sheller Performance Parametres at Different Variable Combinations (9 % MC)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	Mm	wb	Kg/h	Eff, %	Eff, %	%	%
1	1	750	30	35	9	550.98	98.51	96.85	4.80	13.65
1	2	750	40	35	9	627.06	98.43	96.34	4.53	12.32
1	3	750	50	35	9	710.13	98.18	96.07	4.26	11.75
1	4	850	30	35	9	646.83	99.16	97.13	5.15	13.89
1	5	850	40	35	9	729.07	98.94	96.86	5.09	12.61
1	6	850	50	35	9	835.80	98.56	96.52	4.75	12.34
1	7	950	30	35	9	678.36	99.85	97.60	5.70	14.07
1	8	950	40	35	9	734.89	99.57	97.37	5.35	13.76
1	9	950	50	35	9	833.82	99.36	97.12	4.70	13.45
1	10	750	30	40	9	530.10	98.35	95.46	4.40	13.71
1	11	750	40	40	9	598.60	98.28	94.77	4.28	12.48
1	12	750	50	40	9	651.56	98.04	94.10	3.95	12.15
1	13	850	30	40	9	626.20	98.67	96.38	4.95	13.91
1	14	850	40	40	9	719.36	98.47	95.83	4.64	13.30
1	15	850	50	40	9	728.79	98.33	95.50	4.50	12.87

1	16	950	30	40	9	669.73	99.46	97.01	5.20	14.26
1	17	950	40	40	9	718.46	99.17	96.95	5.03	13.99
1	18	950	50	40	9	757.39	99.02	96.21	4.85	13.55
1	19	750	30	45	9	522.16	98.23	95.04	4.20	14.02
1	20	750	40	45	9	581.83	98.11	94.03	4.05	12.85
1	21	750	50	45	9	627.75	97.93	93.78	3.30	12.31
1	22	850	30	45	9	622.22	98.73	95.80	4.50	14.21
1	23	850	40	45	9	705.09	98.51	95.03	4.20	13.53
1	24	850	50	45	9	716.71	98.14	94.83	3.91	13.18
1	25	950	30	45	9	652.42	99.26	96.17	4.70	14.36
1	26	950	40	45	9	670.91	98.94	95.41	4.45	14.15
1	27	950	50	45	9	725.81	98.65	93.50	3.96	13.73

APPENDIX I (contd)

Model Validation Data

Table AI -13: Sheller Performance Parametres at Different Variable Combinations (9 % MC)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	Mm	wb	Kg/h	Eff, %	Eff, %	%	%
2	1	750	30	35	9	567.06	98.52	96.83	4.80	13.61
2	2	750	40	35	9	595.72	98.42	96.37	4.50	12.35
2	3	750	50	35	9	691.51	98.17	97.06	4.23	11.79
2	4	850	30	35	9	660.08	99.17	97.10	5.05	13.93
2	5	850	40	35	9	750.19	98.95	96.85	4.95	12.58
2	6	850	50	35	9	855.84	98.54	96.53	4.60	12.30
2	7	950	30	35	9	716.19	99.83	97.57	5.65	14.10
2	8	950	40	35	9	725.59	99.56	96.34	5.32	13.71
2	9	950	50	35	9	858.60	99.37	96.99	4.75	13.41
2	10	750	30	40	9	547.80	98.37	95.49	4.38	13.69
2	11	750	40	40	9	570.60	98.26	94.75	4.31	12.50
2	12	750	50	40	9	621.02	98.06	94.11	4.05	12.19
2	13	850	30	40	9	640.17	98.65	96.40	4.92	13.89
2	14	850	40	40	9	656.15	98.45	95.85	4.65	13.30

2	15	850	50	40	9	703.65	98.34	95.51	4.45	12.89
2	16	950	30	40	9	661.64	99.47	97.00	5.18	14.26
2	17	950	40	40	9	717.58	99.17	96.97	5.00	14.03
2	18	950	50	40	9	776.67	99.00	96.19	4.88	13.47
2	19	750	30	45	9	551.76	98.24	95.03	4.20	14.06
2	20	750	40	45	9	560.96	98.10	94.00	4.02	12.86
2	21	750	50	45	9	589.62	97.92	93.75	3.35	12.46
2	22	850	30	45	9	620.46	98.74	95.81	4.50	14.23
2	23	850	40	45	9	643.15	98.50	95.05	4.18	13.61
2	24	850	50	45	9	655.79	98.23	94.87	3.90	13.25
2	25	950	30	45	9	661.09	99.27	96.15	4.72	14.30
2	26	950	40	45	9	684.29	98.96	95.42	4.47	14.24
2	27	950	50	45	9	740.57	98.67	93.49	3.95	13.63

APPENDIX I (contd)

Model Validation Data

Table AI -14: Sheller Performance Parametres at Different Variable Combinations (9 %MC)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	mm	wb	Kg/h	Eff, %	Eff, %	%	%
3	1	750	30	35	9	562.98	98.52	96.86	4.90	13.65
3	2	750	40	35	9	624.06	98.44	96.35	4.55	12.32
3	3	750	50	35	9	716.61	98.16	96.07	4.28	11.74
3	4	850	30	35	9	644.99	99.19	97.15	5.15	13.96
3	5	850	40	35	9	727.66	98.95	96.85	5.05	12.61
3	6	850	50	35	9	847.80	98.53	96.53	4.72	12.36
3	7	950	30	35	9	678.36	99.83	97.60	5.75	14.07
3	8	950	40	35	9	727.69	99.55	97.35	5.33	13.69
3	9	950	50	35	9	841.66	99.10	97.10	4.66	13.45
3	10	750	30	40	9	549.06	98.40	95.43	4.40	13.75
3	11	750	40	40	9	564.24	98.30	94.76	4.24	12.50
3	12	750	50	40	9	639.43	98.03	94.12	3.95	12.14

3	13	850	30	40	9	630.16	98.68	96.41	4.92	13.84
3	14	850	40	40	9	663.48	98.50	95.84	4.65	13.42
3	15	850	50	40	9	713.52	98.29	95.47	4.55	12.83
3	16	950	30	40	9	709.31	99.47	97.07	5.18	14.14
3	17	950	40	40	9	714.03	99.22	96.97	5.00	14.03
3	18	950	50	40	9	756.13	99.06	96.25	4.80	13.47
3	19	750	30	45	9	540.72	98.24	95.08	4.25	14.04
3	20	750	40	45	9	551.81	98.14	94.03	4.10	12.84
3	21	750	50	45	9	604.31	97.94	93.80	3.30	12.32
3	22	850	30	45	9	601.70	98.74	95.80	4.53	14.16
3	23	850	40	45	9	626.31	98.50	95.08	4.24	13.51
3	24	850	50	45	9	692.20	98.18	94.82	3.94	13.28
3	25	950	30	45	9	708.02	99.29	96.17	4.68	14.30
3	26	950	40	45	9	714.50	98.95	95.40	4.42	14.24
3	27	950	50	45	9	745.56	98.68	93.50	3.95	13.69

APPENDIX I (contd)

Model Validation Data

Table AI -15: Sheller Performance Parametres at Different Variable Combinations (12 % MC)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	Mm	wb	Kg/h	Eff, %	Eff, %	%	%
1	1	750	30	35	12	513.04	98.31	95.87	4.20	14.09
1	2	750	40	35	12	542.13	98.01	95.28	3.87	13.66
1	3	750	50	35	12	590.85	97.83	94.92	3.65	13.27
1	4	850	30	35	12	571.86	98.66	96.77	4.40	14.42
1	5	850	40	35	12	618.67	98.54	96.25	4.25	14.04
1	6	850	50	35	12	670.94	98.29	95.94	4.20	13.74
1	7	950	30	35	12	658.05	99.17	97.25	4.75	14.70
1	8	950	40	35	12	680.71	98.98	96.85	4.42	14.36
1	9	950	50	35	12	691.51	98.87	96.63	4.25	14.02
1	10	750	30	40	12	509.12	98.22	95.12	3.88	14.35
1	11	750	40	40	12	535.40	97.89	94.37	3.55	13.91
1	12	750	50	40	12	559.76	97.61	94.05	3.25	13.76

1	13	850	30	40	12	549.96	98.53	96.06	4.20	14.67
1	14	850	40	40	12	598.68	98.32	95.45	3.80	14.32
1	15	850	50	40	12	609.31	98.08	94.90	3.51	13.94
1	16	950	30	40	12	600.44	98.95	95.61	4.55	14.82
1	17	950	40	40	12	637.79	98.70	95.22	4.10	14.58
1	18	950	50	40	12	694.80	98.48	94.86	3.77	14.09
1	19	750	30	45	12	497.60	97.61	94.76	3.50	14.76
1	20	750	40	45	12	518.60	97.34	94.44	3.20	14.31
1	21	750	50	45	12	532.55	97.11	93.66	3.00	14.06
1	22	850	30	45	12	554.94	97.96	95.36	3.74	14.96
1	23	850	40	45	12	581.47	97.71	94.88	3.50	14.69
1	24	850	50	45	12	612.00	97.49	94.48	3.15	14.31
1	25	950	30	45	12	610.47	98.58	95.82	4.00	15.14
1	26	950	40	45	12	630.18	98.26	95.20	3.65	14.81
1	27	950	50	45	12	646.47	97.94	93.16	3.37	14.58

APPENDIX I (contd)

Model Validation Data

Table AI -16: Sheller Performance Parametres at Different Variable Combinations (12 %)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	mm	wb	Kg/h	Eff, %	Eff, %	%	%
2	1	750	30	35	12	518.40	98.29	95.87	4.20	14.05
2	2	750	40	35	12	557.88	97.99	95.31	3.85	13.63
2	3	750	50	35	12	579.91	97.84	94.91	3.60	13.34
2	4	850	30	35	12	564.53	98.68	96.81	4.35	14.45
2	5	850	40	35	12	602.73	98.51	96.28	4.24	14.09
2	6	850	50	35	12	673.20	98.21	95.98	4.15	13.74
2	7	950	30	35	12	653.86	99.20	97.28	4.70	14.69
2	8	950	40	35	12	677.53	99.03	96.88	4.40	14.31
2	9	950	50	35	12	698.81	98.89	96.67	4.20	14.03
2	10	750	30	40	12	515.72	98.12	95.11	3.85	14.37
2	11	750	40	40	12	542.72	97.86	95.36	3.52	13.88
2	12	750	50	40	12	553.92	97.64	94.09	3.25	13.69

2	13	850	30	40	12	552.31	98.46	96.04	4.18	14.67
2	14	850	40	40	12	601.91	98.21	95.48	3.76	14.31
2	15	850	50	40	12	617.18	98.03	94.93	3.50	13.93
2	16	950	30	40	12	626.23	98.91	95.63	4.54	14.73
2	17	950	40	40	12	687.57	98.65	95.21	4.07	14.52
2	18	950	50	40	12	690.74	98.41	94.87	3.75	13.95
2	19	750	30	45	12	503.20	97.65	94.76	3.45	14.77
2	20	750	40	45	12	524.61	97.35	94.46	3.20	14.30
2	21	750	50	45	12	540.40	97.13	93.67	3.00	14.02
2	22	850	30	45	12	559.80	97.95	95.38	3.72	14.92
2	23	850	40	45	12	571.59	97.72	94.91	3.48	14.65
2	24	850	50	45	12	595.89	97.51	94.45	3.12	14.32
2	25	950	30	45	12	644.98	98.60	95.80	3.98	15.13
2	26	950	40	45	12	679.58	98.30	95.18	3.65	14.87
2	27	950	50	45	12	691.61	97.88	93.19	3.35	14.55

APPENDIX I (contd)

Model Validation Data

Table AI -17: Sheller Performance Parametres at Different Variable Combinations (12 % MC)

REP	OBS	SPD	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		rpm	Kg/min	Mm	wb	Kg/h	Eff, %	Eff, %	%	%
3	1	750	30	35	12	510.72	98.30	95.85	4.24	14.05
3	2	750	40	35	12	538.96	98.00	95.26	3.90	13.63
3	3	750	50	35	12	582.32	97.81	94.94	3.66	13.34
3	4	850	30	35	12	566.30	98.67	96.73	4.45	14.45
3	5	850	40	35	12	616.91	98.51	96.28	4.30	14.09
3	6	850	50	35	12	686.48	98.26	95.93	4.20	13.74
3	7	950	30	35	12	639.69	99.20	97.21	4.78	14.69
3	8	950	40	35	12	656.59	98.97	96.86	4.45	14.31
3	9	950	50	35	12	671.45	98.82	96.60	4.27	14.03
3	10	750	30	40	12	516.82	98.21	95.10	3.90	14.37

3	11	750	40	40	12	546.76	97.87	94.34	3.58	13.88
3	12	750	50	40	12	558.09	97.63	94.03	3.30	13.69
3	13	850	30	40	12	577.51	98.56	96.09	4.22	14.67
3	14	850	40	40	12	599.18	98.34	95.43	3.85	14.31
3	15	850	50	40	12	613.39	98.03	94.86	3.52	13.93
3	16	950	30	40	12	616.07	98.96	95.59	4.55	14.73
3	17	950	40	40	12	689.08	98.74	95.25	4.15	14.52
3	18	950	50	40	12	706.02	98.50	94.84	3.78	13.95
3	19	750	30	45	12	508.14	97.62	94.78	3.54	14.77
3	20	750	40	45	12	525.79	97.36	94.48	3.24	14.30
3	21	750	50	45	12	548.05	97.12	93.64	3.05	14.02
3	22	850	30	45	12	582.80	97.94	95.40	3.75	14.92
3	23	850	40	45	12	603.31	97.72	94.85	3.54	14.65
3	24	850	50	45	12	621.23	97.50	94.45	3.18	14.32
3	25	950	30	45	12	651.28	98.59	95.83	4.00	15.13
3	26	950	40	45	12	674.13	98.25	95.18	3.68	14.87
3	27	950	50	45	12	690.25	97.96	93.17	3.40	14.55

APPENDIX I (contd)

Model Validation Data

Table AI -18: Sheller Performance Parametres at Different Variable Combinations (15 % MC)

REP	OBS	FDR	CLR	MC %,	Output,	Shelling	Cleaning	Damage	SCLoss
		Kg/min	mm	wb	Kg/h	Eff, %	Eff, %	%	%
1	1	30	35	15	412.77	97.70	92.80	3.88	16.29
1	2	40	35	15	444.80	97.31	92.39	3.55	15.68
1	3	50	35	15	474.29	97.00	92.00	3.28	15.23
1	4	30	35	15	468.49	98.35	93.10	4.15	16.77
1	5	40	35	15	470.52	98.04	92.69	4.00	16.44
1	6	50	35	15	493.78	97.61	92.33	3.85	16.03
1	7	30	35	15	505.41	98.81	93.76	4.50	17.05
1	8	40	35	15	531.85	98.56	93.20	4.15	16.61

1	9	50	35	15	557.38	98.24	92.86	3.84	16.25
1	10	30	40	15	388.77	97.59	92.34	3.52	16.71
1	11	40	40	15	426.80	97.35	92.01	3.22	15.89
1	12	50	40	15	448.22	96.74	91.60	2.95	15.45
1	13	30	40	15	436.47	97.99	92.66	3.90	17.02
1	14	40	40	15	449.80	97.79	92.19	3.40	16.81
1	15	50	40	15	464.73	97.54	91.74	3.15	16.33
1	16	30	40	15	484.30	98.55	93.12	4.20	17.45
1	17	40	40	15	507.66	98.25	92.71	3.80	16.96
1	18	50	40	15	537.51	97.90	92.31	3.41	16.51
1	19	30	45	15	374.25	97.00	91.67	3.14	16.97
1	20	40	45	15	395.95	96.76	91.23	2.92	16.43
1	21	50	45	15	424.76	96.50	90.58	2.60	15.96
1	22	30	45	15	450.92	97.44	92.09	3.44	17.30
1	23	40	45	15	426.15	97.21	91.59	3.10	17.04
1	24	50	45	15	466.27	96.96	91.03	2.86	16.76
1	25	30	45	15	463.91	98.02	91.79	3.75	17.61
1	26	40	45	15	477.26	97.67	91.29	3.30	17.48
1	27	50	45	15	500.12	97.40	90.80	3.00	17.09

APPENDIX I (contd)

Model Validation Data

Table AI -19: Sheller Performance Parametres at Different Variable Combinations (15 % MC)

REP	OBS	FDR Kg/min	CLR mm	MC %, wb	Output, Kg/h	Shelling Eff, %	Cleaning Eff, %	Damage %	SCLoss %
2	1	30	35	15	425.29	97.68	92.84	3.85	16.32
2	2	40	35	15	455.96	97.32	92.38	3.50	15.71
2	3	50	35	15	475.59	97.02	92.04	3.25	15.24
2	4	30	35	15	470.88	98.34	93.09	4.15	16.70
2	5	40	35	15	478.80	98.00	92.66	3.98	16.41
2	6	50	35	15	503.24	97.62	92.29	3.80	16.04
2	7	30	35	15	505.69	98.80	93.78	4.46	17.07

2	8	40	35	15	529.04	98.53	93.23	4.12	16.62
2	9	50	35	15	556.20	98.24	92.88	3.00	16.27
2	10	30	40	15	389.43	97.58	92.38	3.50	16.73
2	11	40	40	15	428.77	97.33	92.06	3.20	15.85
2	12	50	40	15	453.42	96.71	91.56	2.94	15.43
2	13	30	40	15	433.41	97.97	92.68	3.85	17.02
2	14	40	40	15	456.51	97.76	92.17	3.36	16.77
2	15	50	40	15	470.84	97.55	91.76	3.12	16.30
2	16	30	40	15	496.88	98.56	93.13	4.18	17.44
2	17	40	40	15	511.63	98.23	92.92	3.75	16.90
2	18	50	40	15	540.39	97.92	92.32	3.40	16.50
2	19	30	45	15	370.48	97.01	91.69	3.11	16.97
2	20	40	45	15	408.81	96.75	91.24	2.90	16.45
2	21	50	45	15	427.73	96.53	90.52	2.50	15.93
2	22	30	45	15	432.34	97.42	92.08	3.40	17.34
2	23	40	45	15	433.86	97.22	91.56	3.05	17.07
2	24	50	45	15	471.15	96.95	91.07	2.85	16.77
2	25	30	45	15	478.01	97.99	91.82	3.70	17.60
2	26	40	45	15	483.62	97.64	91.34	3.26	17.50
2	27	50	45	15	508.93	97.39	90.83	2.95	17.09

APPENDIX I (contd)

Model Validation Data

Table AI -20: Sheller Performance Parametres at Different Variable Combinations (15 % MC)

REP	OBS	FDR	CLR	MC	Output,	Shelling	Cleaning	Damage	SCLoss
		Kg/min	mm	%, wb	Kg/h	Eff, %	Eff, %	%	%
3	1	30	35	15	424.44	97.71	92.81	3.85	16.34
3	2	40	35	15	449.41	97.32	92.36	3.60	15.74
3	3	50	35	15	470.85	97.01	91.98	3.30	15.26
3	4	30	35	15	461.48	98.32	93.08	4.15	16.73
3	5	40	35	15	474.70	98.02	92.67	4.05	16.43
3	6	50	35	15	499.63	97.63	92.35	3.86	16.02

3	7	30	35	15	494.85	98.79	93.79	4.50	17.04
3	8	40	35	15	535.83	98.58	93.18	4.20	16.61
3	9	50	35	15	561.44	98.28	92.90	3.05	16.21
3	10	30	40	15	400.06	97.61	92.29	3.55	16.66
3	11	40	40	15	433.58	97.33	91.99	3.25	15.82
3	12	50	40	15	458.43	96.72	91.70	3.00	15.43
3	13	30	40	15	443.15	97.98	92.64	3.90	17.01
3	14	40	40	15	457.88	97.80	92.20	3.50	16.78
3	15	50	40	15	485.95	97.50	91.76	3.20	16.32
3	16	30	40	15	494.48	98.51	93.14	4.25	17.40
3	17	40	40	15	515.68	98.21	92.80	3.85	16.89
3	18	50	40	15	531.88	97.86	92.30	3.45	16.53
3	19	30	45	15	389.61	97.04	91.68	3.15	17.03
3	20	40	45	15	405.34	96.78	91.16	2.95	16.35
3	21	50	45	15	420.09	96.52	90.52	2.60	15.99
3	22	30	45	15	449.76	97.42	92.14	3.45	17.33
3	23	40	45	15	429.73	97.18	91.62	3.15	17.03
3	24	50	45	15	488.78	96.94	91.06	2.89	16.71
3	25	30	45	15	449.15	98.01	91.89	3.75	17.64
3	26	40	45	15	484.84	97.69	91.46	3.30	17.47
3	27	50	45	15	492.18	97.36	90.95	3.00	17.15

Appendix II: ANALYSIS OF VARIANCE (ANOVA) OUTPUT

Table AII- 1: ANOVA for Physical Properties of Different Varieties of Maize at Different Moisture Contents

Length

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	4	0.00004947	0.00001237	0.44	2.67
VAR	2	0.20310773	0.10155387	3594.30	3.30
MC	2	0.09028493	0.04514247	1597.73	3.30
VAR*MC	4	0.00687253	0.00171813	60.81	2.67

WIDTH

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	4	0.00012320	0.00003080	0.02	2.67
VAR	2	0.34433444	0.17216722	98.83	3.30

MC	2	0.26157991	0.13078996	75.08	3.30
VAR*MC	4	0.00311916	0.00077979	0.45	2.67

Thickness

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	4	0.00012436	0.00003109	0.50	2.67
VAR	2	0.01666698	0.00833349	133.63	3.30
MC	2	0.03059324	0.01529662	245.28	3.30
VAR*MC	4	0.00137436	0.00034359	5.51	2.67

Bulk density

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	4	52.61911	13.15478	0.31	2.67
VAR	2	62624.43911	31312.21956	743.12	3.30
MC	2	97421.76178	48710.88089	1156.03	3.30
VAR*MC	4	13941.11822	3485.27956	82.71	2.67

A Thousand grain mass

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	4	72.54741	18.13685	0.75	2.67
VAR	2	60607.28133	30303.64067	1250.24	3.30
MC	2	11784.20233	5892.10117	243.09	3.30
VAR*MC	4	703.51501	175.87875	7.26	2.67

Geometric mean diameter

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	4	0.00016569	0.00004142	0.65	2.67
VAR	2	0.08929333	0.04464667	698.04	3.30
MC	2	0.07052813	0.03526407	551.35	3.30
VAR*MC	4	0.00799093	0.00199773	31.23	2.67

Rep= Replication, VAR= Variety, MC = Moisture Content DF = deg of Freedom

Table AII- 2: ANOVA for Output capacity for Model Development Data

Source	DF	Sum of squares	Mean Square	F calc	F table (5 %)
REP	2	76.983	38.492	0.23	3.05
SPD	2	1382343.120	691171.560	4105.58	3.05
FDR	2	876304.303	438152.152	2602.64	3.05
CLR	2	253717.231	126858.615	753.54	3.05
MC	2	1228185.051	614092.526	3647.73	3.05
SPD*FDR	4	44305.116	11076.279	65.79	2.42
SPD*CLR	4	2235.804	558.951	3.32	2.42
SPD*MC	4	59202.065	14800.516	87.92	2.42
FDR*CLR	4	3852.790	963.198	5.72	2.42
FDR*MC	4	2545.719	636.430	3.78	2.42
CLR*MC	4	6126.093	1531.523	9.10	2.42
SPD*FDR*CLR	8	934.061	116.758	0.69	2.00
SPD*FDR*MC	8	62968.366	7871.046	46.75	2.00
SPD*CLR*MC	8	765.279	95.660	0.57	2.00
FDR*CLR*MC	8	396.379	49.547	0.29	2.00
SPD*FDR*CLR*MC	16	2636.398	164.775	0.98	1.70

Error	160	26935.883	168.349
Total	242	3953530.641	

Table AII- 3: ANOVA for Shelling efficiency for Model Development Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	0.13626667	0.06813333	1.37	3.05
SPD	2	66.36236296	33.18118148	669.59	3.05
FDR	2	16.47209630	8.23604815	166.20	3.05
CLR	2	16.58471852	8.29235926	167.34	3.05
MC	2	33.76614074	16.88307037	340.70	3.05
SPD*FDR	4	0.18585926	0.04646481	0.94	2.42
SPD*CLR	4	0.04857037	0.01214259	0.25	2.42
SPD*MC	4	0.13121481	0.03280370	0.66	2.42
FDR*CLR	4	0.02590370	0.00647593	0.13	2.42
FDR*MC	4	0.03214815	0.00803704	0.16	2.42
CLR*MC	4	0.45825926	0.11456481	2.31	2.42
SPD*FDR*CLR	8	0.02100741	0.00262593	0.05	2.00
SPD*FDR*MC	8	0.02829630	0.00353704	0.07	2.00
SPD*CLR*MC	8	0.05485185	0.00685648	0.14	2.00
FDR*CLR*MC	8	0.01045185	0.00130648	0.03	2.00
SPD*FDR*CLR*MC	16	0.04783704	0.00298981	0.06	1.70
Error	160	7.92873330	0.04955460		
Total	242	142.29471850			

Table AII- 4: ANOVA for Cleaning efficiency for Model Development Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	0.920289	0.460144	2.10	3.05
SPD	2	4509.677356	2254.838678	10294.10	3.05
FDR	2	119.950200	59.975100	273.81	3.05
CLR	2	171.771467	85.885733	392.10	3.05
MC	2	1182.694489	591.347244	2699.70	3.05
SPD*FDR	4	7.178444	1.794611	8.19	2.42
SPD*CLR	4	21.044978	5.261244	24.02	2.42
SPD*MC	4	157.249422	39.312356	179.47	2.42
FDR*CLR	4	6.337867	1.584467	7.23	2.42
FDR*MC	4	3.265844	0.816461	3.73	2.42
CLR*MC	4	7.317044	1.829261	8.35	2.42
SPD*FDR*CLR	8	13.354556	1.669319	7.62	2.00
SPD*FDR*MC	8	14.625311	1.828164	8.35	2.00
SPD*CLR*MC	8	15.977111	1.997139	9.12	2.00
FDR*CLR*MC	8	7.143556	0.892944	4.08	2.00
SPD*FDR*CLR*MC	16	23.149422	1.446839	6.61	1.70

Error	160	35.046711	0.219042		
Total	242	6296.704067			

Table AII- 5: ANOVA for Grain Damage for Model Development Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	0.0046840	0.0023420	3.87	3.05
SPD	2	114.8930296	57.4465148	94839.20	3.05
FDR	2	46.2694296	23.1347148	38193.40	3.05
CLR	2	11.9059852	5.9529926	9827.87	3.05
MC	2	73.2938741	36.6469370	60500.90	3.05
SPD*FDR	4	3.0613704	0.7653426	1263.51	2.42
SPD*CLR	4	0.0198815	0.0049704	8.21	2.42
SPD*MC	4	9.7430593	2.4357648	4021.24	2.42
FDR*CLR	4	0.2196815	0.0549204	90.67	2.42
FDR*MC	4	9.2134593	2.3033648	3802.66	2.42
CLR*MC	4	0.1971704	0.0492926	81.38	2.42
SPD*FDR*CLR	8	0.3664519	0.0458065	75.62	2.00
SPD*FDR*MC	8	1.9662074	0.2457759	405.75	2.00
SPD*CLR*MC	8	0.3340296	0.0417537	68.93	2.00
FDR*CLR*MC	8	0.3294296	0.0411787	67.98	2.00
SPD*FDR*CLR*MC	16	0.8883704	0.0555231	91.66	1.70
Error	160	0.0969160	0.0006057		
Total	242	272.8030296			

Table AII- 6: ANOVA for Scatter Loss for Model **Development** Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	0.00527654	0.00263827	3.88	3.05
SPD	2	80.36845185	40.18422593	59027.50	3.05
FDR	2	35.68605185	17.84302593	26210.00	3.05
CLR	2	48.83849630	24.41924815	35870.00	3.05
MC	2	58.73969630	29.36984815	43142.00	3.05
SPD*FDR	4	0.49852593	0.12463148	183.07	2.42
SPD*CLR	4	3.29454815	0.82363704	1209.86	2.42
SPD*MC	4	3.14574815	0.78643704	1155.21	2.42
FDR*CLR	4	0.92021481	0.23005370	337.93	2.42
FDR*MC	4	0.63021481	0.15755370	231.43	2.42
CLR*MC	4	20.36357037	5.09089259	7478.12	2.42
SPD*FDR*CLR	8	0.43847407	0.05480926	80.51	2.00
SPD*FDR*MC	8	0.45887407	0.05735926	84.26	2.00
SPD*CLR*MC	8	4.40865185	0.55108148	809.50	2.00
FDR*CLR*MC	8	0.33311852	0.04163981	61.17	2.00
SPD*FDR*CLR*MC	16	0.73372593	0.04585787	67.36	1.70
Error	160	0.10892350	0.00068080		
Total	242	258.97256300			

Table AII- 7: ANOVA for Output Capacity for Model **Validation** Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	650.752	325.376	1.71	3.05
SPD	2	527939.304	263969.652	1384.70	3.05
FDR	2	196337.445	98168.722	514.96	3.05
CLR	2	81550.871	40775.436	213.90	3.05
MC	2	1756476.673	878238.337	4606.97	3.05
SPD*FDR	4	342.196	85.549	0.45	2.42
SPD*CLR	4	3038.036	759.509	3.98	2.42
SPD*MC	4	32662.876	8165.719	42.83	2.42
FDR*CLR	4	15892.279	3973.070	20.84	2.42
FDR*MC	4	31417.817	7854.454	41.20	2.42
CLR*MC	4	15067.636	3766.909	19.76	2.42
SPD*FDR*CLR	8	2651.189	331.399	1.74	2.00
SPD*FDR*MC	8	4567.098	570.887	2.99	2.00
SPD*CLR*MC	8	4648.744	581.093	3.05	2.00
FDR*CLR*MC	8	12631.391	1578.924	8.28	2.00
SPD*FDR*CLR*MC	16	4674.157	292.135	1.53	1.70
Error	160	30501.193	190.632		
Total	242	2721049.656			

Table AII- 8: ANOVA for Shelling Efficiency for Model Validation Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	0.00212099	0.00106049	1.29	3.05
SPD	2	39.23351358	19.61675679	23908.50	3.05
FDR	2	10.86849630	5.43424815	6623.14	3.05
CLR	2	16.52178025	8.26089012	10068.20	3.05
MC	2	45.91198025	22.95599012	27978.30	3.05
SPD*FDR	4	0.02936049	0.00734012	8.95	2.42
SPD*CLR	4	0.40246914	0.10061728	122.63	2.42
SPD*MC	4	0.36541728	0.09135432	111.34	2.42
FDR*CLR	4	0.00517531	0.00129383	1.58	2.42
FDR*MC	4	0.20257531	0.05064383	61.72	2.42
CLR*MC	4	1.44817284	0.36204321	441.25	2.42
SPD*FDR*CLR	8	0.19591605	0.02448951	29.85	2.00
SPD*FDR*MC	8	0.18045679	0.02255710	27.49	2.00
SPD*CLR*MC	8	0.24106667	0.03013333	36.73	2.00
FDR*CLR*MC	8	0.16335309	0.02041914	24.89	2.00
SPD*FDR*CLR*MC	16	0.07553333	0.00472083	5.75	1.70
Error	160	0.13127900	0.00082050		
Total	242	115.9786667			

Table AII- 9: ANOVA for Cleaning Efficiency for Model Validation Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	0.0165358	0.0082679	0.61	3.05
SPD	2	33.0549654	16.5274827	1227.71	3.05
FDR	2	42.4298691	21.2149346	1575.90	3.05
CLR	2	113.1444222	56.5722111	4202.34	3.05
MC	2	643.5030222	321.7515111	23900.6	3.05
SPD*FDR	4	1.0022617	0.2505654	18.61	2.42
SPD*CLR	4	5.1915309	1.2978827	96.41	2.42
SPD*MC	4	3.0542049	0.7635512	56.72	2.42
FDR*CLR	4	3.9284346	0.9821086	72.95	2.42
FDR*MC	4	0.4801679	0.1200420	8.92	2.42
CLR*MC	4	5.3025037	1.3256259	98.47	2.42
SPD*FDR*CLR	8	3.4982568	0.4372821	32.48	2.00
SPD*FDR*MC	8	0.7481383	0.0935173	6.95	2.00
SPD*CLR*MC	8	6.4695802	0.8086975	60.07	2.00
FDR*CLR*MC	8	1.1830543	0.1478818	10.99	2.00
SPD*FDR*CLR*MC	16	2.5289284	0.1580580	11.74	1.70
Error	160	2.1539309	0.0134621		
Total	242	867.6898074			

Table AII- 10: ANOVA for Grain Damage for Model Validation Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	0.08748889	0.04374444	12.76	3.05
SPD	2	12.82095556	6.41047778	1870.16	3.05
FDR	2	15.19606667	7.59803333	2216.61	3.05
CLR	2	23.02237284	11.51118642	3358.21	3.05
MC	2	48.70342469	24.35171235	7104.23	3.05
SPD*FDR	4	0.42994074	0.10748519	31.36	2.42
SPD*CLR	4	0.35407160	0.08851790	25.82	2.42
SPD*MC	4	0.28088642	0.07022160	20.49	2.42
FDR*CLR	4	0.07504938	0.01876235	5.47	2.42
FDR*MC	4	0.18049383	0.04512346	13.16	2.42
CLR*MC	4	0.11709877	0.02927469	8.54	2.42
SPD*FDR*CLR	8	0.51241728	0.06405216	18.69	2.00
SPD*FDR*MC	8	0.17563951	0.02195494	6.41	2.00
SPD*CLR*MC	8	0.23481975	0.02935247	8.56	2.00
FDR*CLR*MC	8	0.51583457	0.06447932	18.81	2.00
SPD*FDR*CLR*MC	16	0.33518025	0.02094877	6.11	1.70
Error	160	0.5484444	0.0034278		
Total	242	103.5901852			

Table AII- 11: ANOVA for Scatter Loss for Model Validation Data

Source	DF	Sum of Squares	Mean Square	F calc	F table (5 %)
REP	2	0.0030543	0.0015272	1.51	3.05
SPD	2	29.6265407	14.8132704	14665.50	3.05
FDR	2	33.4710914	16.7355457	16568.60	3.05
CLR	2	14.6754840	7.3377420	7264.54	3.05
MC	2	450.4590543	225.2295272	222982.00	3.05
SPD*FDR	4	2.2537679	0.5634420	557.82	2.42
SPD*CLR	4	0.1482864	0.0370716	36.70	2.42
SPD*MC	4	2.6640049	0.6660012	659.36	2.42
FDR*CLR	4	0.2753580	0.0688395	68.15	2.42
FDR*MC	4	2.0720099	0.5180025	512.83	2.42
CLR*MC	4	0.3217951	0.0804488	79.65	2.42
SPD*FDR*CLR	8	0.2851901	0.0356488	35.29	2.00
SPD*FDR*MC	8	1.6600716	0.2075090	205.44	2.00
SPD*CLR*MC	8	0.4257309	0.0532164	52.69	2.00
FDR*CLR*MC	8	0.3099037	0.0387380	38.35	2.00
SPD*FDR*CLR*MC	16	0.3021630	0.0188852	18.70	1.70
Error	160	0.1616123	0.0010101		
Total	242	539.1151185			

Appendix III: Computation of Model Parameters

Shelling prediction computations

$$\pi_1 = k\,(\pi_1)_{\overline{3}}\,(\pi_1)_{\overline{2}} \qquad \text{(AIII.1)}$$

$$(\pi_1)_{\overline{2}} = 0.061\,\pi_2^{\,0.52} \qquad \text{(AIII.2)}$$

$$(\pi_1)_{\overline{3}} = 0.163\,\pi_3^{\,0.69} \qquad \text{(AIII.3)}$$

$$\bar{\pi}_2 = 0.061\,(16.075)^{0.52} = 0.25854$$

$$k = \frac{1}{0.25854} = 3.868$$

$$\pi_1 = \lambda_S C\,,\ \pi_2 = \frac{\rho V C^2}{F} \text{ and } \pi_3 = \frac{C}{DM}$$

Substituting the values in AIII.1:

$$\lambda_S C = 3.868\ (0.061)\ (0.163)\left(\frac{\rho V C^2}{F}\right)^{0.52}\left(\frac{C}{DM}\right)^{0.69} \quad \text{(AIII.4)}$$

$$\lambda_S = 0.0385\left(\frac{\rho V}{F}\right)^{0.52}\left(\frac{1}{DM}\right)^{0.69}(c)^{1.04+0.69-1.0} \quad \text{(AIII.5)}$$

$$\lambda_S = 0.0385\left(\frac{\rho V}{F}\right)^{0.52}\left(\frac{1}{DM}\right)^{0.69}(c)^{0.73} \quad \text{(AIII.6)}$$

Grain damage prediction computations

$$\pi_1 = k\ (\pi_1)_{\overline{3}}\ (\pi_1)_{\overline{2}} \quad \text{(AIII.7)}$$

$$(\pi_1)_{\overline{2}} = 0.00020\ \pi_2^{0.95} \quad \text{(AIII.8)}$$

$$(\pi_1)_{\overline{3}} = 0.00174\ \pi_3^{0.78} \quad \text{(AIII.9)}$$

$$\bar{\pi}_2 = 0.00020\ (17.538)^{0.95} = 0.00304$$

$$\text{k} = \frac{1}{0.00304} = 328.995$$

$\pi_1 = \lambda_D C$, $\pi_2 = \frac{F}{\rho V C^2}$, and $\pi_3 = \frac{DM}{C}$

Substituting the values in AIII.7:

$$\lambda_D C = 328.995\ (0.00020)\ (0.00174)\left(\frac{\rho V C^2}{F}\right)^{0.95}\left(\frac{C}{DM}\right)^{0.78} \quad \text{(AIII.10)}$$

$$\lambda_D = 0.0001145\left(\frac{\rho V}{F}\right)^{0.95}\left(\frac{1}{DM}\right)^{0.78}(c)^{1.90+0.78-1.0} \quad \text{(AIII.11)}$$

$$\lambda_S = 0.000115\left(\frac{\rho V}{F}\right)^{0.95}\left(\frac{1}{DM}\right)^{0.78}(c)^{1.68} \quad \text{(AIII.12)}$$

Scattered Grain Loss Prediction computations

$$\pi_1 = k\ (\pi_1)_{\overline{3}}\ (\pi_1)_{\overline{2}} \quad \text{(AIII.13)}$$

$$(\pi_1)_{\overline{2}} = 0.651\ \pi_2^{-0.48} \quad \text{(AIII.14)}$$

$$(\pi_1)_{\overline{3}} = 0.198\pi_3^{-0.33} \quad \text{(AIII.15)}$$

$$\bar{\pi}_2 = 0.651\ (19.00)^{-0.48} = 0.1584$$

$k = \frac{1}{0.1584} = 6.3128$

$\pi_1 = \beta C$, $\pi_2 = \frac{\rho V C^2}{F}$ and $\pi_3 = \frac{C}{DM}$

Substituting the values in AIII.13:

$$\beta C = 6.3128\ (0.651)\ (0.198)\left(\frac{\rho V C^2}{F}\right)^{-0.48}\left(\frac{C}{DM}\right)^{-0.33} \quad \text{(AIII.16)}$$

$$\beta = 0.81\left(\frac{\rho V}{F}\right)^{-0.48}\left(\frac{1}{DM}\right)^{-0.33}(c)^{-0.96-0.33-1.0} \quad \text{(AIII.17)}$$

$$\beta = 0.81\left(\frac{F}{\rho V}\right)^{0.48}(DM)^{0.33}\left(\frac{1}{C}\right)^{2.29} \quad \text{(AIII.18)}$$

Table AIII-1: Computation of *RMSE, Bias, SB* and *d*

Measurd	Prdict					A	B	
M	P	P-M	$(P-M)^2$	$P-\bar{M}$	$O-\bar{M}$	$\lvert P-\bar{M}\rvert$	$\lvert O-\bar{M}\rvert$	$(A+B)^2$
98.43	98.55	0.1200	0.0144	0.26	0.14	0.26	0.1400	0.1600
98.04	98.47	0.4300	0.1849	0.18	-0.25	0.18	0.2500	0.1849
99.47	99.80	0.3300	0.1089	1.51	1.18	1.51	1.1800	7.2361
99.03	99.14	0.1100	0.0121	0.85	0.74	0.85	0.7400	2.5281
99.27	99.88	0.6100	0.3721	1.59	0.98	1.59	0.9800	6.6049

98.18	98.57	0.3900	0.1521	0.28	-0.11	0.28	0.1100	0.1521
97.12	97.15	0.0300	0.0009	-1.14	-1.17	1.14	1.1700	5.3361
99.84	99.64	-0.2000	0.0400	1.35	1.55	1.35	1.5500	8.4100
97.20	97.13	-0.0700	0.0049	-1.16	-1.09	1.16	1.0900	5.0625
$\bar{M}$ =98.29	$\bar{P}$=98.56	Σ=1.75	Σ=0.890				Σ= 1.97	Σ=34.875

RMSE = $\sqrt{\frac{1}{9}(0.890)}$ = 0.314

Bias = $\frac{1}{9}(1.75)$ = 0.194

d = $1 - \frac{0.890}{34.875}$ = 0.974

SB = $(98.56-98.29)^2$ = 0.0729

Table AIII-2: Computation of values of t statistic for inference on slope and intercept hypotheses (Shelling)

Measured	Predicted	x deviates	y deviates	Square x deviates	Square y deviates	Product xy deviates
x	y	x-$\bar{x}$	y-$\bar{y}$	x^2	y^2	xy
98.43	98.55	0.1400	-0.0100	0.0196	0.0001	-0.0014
98.04	98.47	-0.2500	-0.0900	0.0625	0.0081	0.0225
99.47	99.80	1.1800	1.2400	1.3924	1.5376	1.4632
99.03	99.14	0.7400	0.5800	0.5476	0.3364	0.4292

99.27	99.88	0.9800	1.3200	0.9604	1.7424	1.2936
98.18	98.57	-0.1100	0.0100	0.0121	0.0001	-0.0011
97.12	97.15	-1.1700	-1.4100	1.3689	1.9881	1.6497
99.84	99.64	1.5500	1.0800	2.4025	1.1664	1.6740
97.20	97.13	-1.0900	-1.4300	1.1881	2.0449	1.5587
$\bar{x} = 98.29$	$\bar{y} = 98.56$			$\boldsymbol{\Sigma}$=7.954	$\boldsymbol{\Sigma}$=8.824	$\boldsymbol{\Sigma}$=8.088

$$S^2{}_{y.x} = \frac{\sum y^2 - \frac{(\sum xy)^2}{\sum x^2}}{n-2} = 1.116$$

$$t_b = \frac{b}{\sqrt{\frac{S^2{}_{y.x}}{\sum x^2}}} = 2.072$$

$$t_\alpha = \frac{\alpha - \alpha_0}{\sqrt{S^2{}_{y.x}\left(\frac{1}{n} + \frac{\bar{x}^2}{\sum x^2}\right)}} = 0.038$$

Appendix III: Computation of Model Evaluation Parameters

Grain Damage

Table AIII-3: Computation of *RMSE, Bias, , SB* and *d*

Measd	Predict					A	B	
M	P	P-M	$(P-M)^2$	$P-\bar{M}$	$O-\bar{M}$	$\lvert P-\bar{M}\rvert$	$\lvert O-\bar{M}\rvert$	$(A+B)^2$
4.83	4.75	-0.08	0.0064	0.44	0.52	0.44	0.52	0.921

5.12	5.38	0.26	0.0676	1.07	0.81	1.07	0.81	3.534
5.70	5.99	0.29	0.0841	1.68	1.39	1.68	1.39	9.424
4.11	4.20	0.09	0.0081	-0.11	-0.20	0.11	0.20	0.096
3.15	3.74	0.59	0.3481	-0.57	-1.16	-0.57	-1.16	2.992
4.38	4.41	0.03	0.0009	0.10	0.07	0.10	0.07	0.028
3.85	4.08	0.23	0.0529	-0.23	-0.46	-0.23	-0.46	0.476
3.69	3.66	-0.03	0.0009	-0.65	-0.62	-0.65	-0.62	1.612
3.98	3.69	-0.29	0.0841	-0.62	-0.33	-0.62	-0.33	0.902
$\bar{M}$ =4.								
31	$\bar{P}$=4.43	Σ=1.09	Σ=1.841				Σ= 0.42	Σ=19.9

RMSE = $\sqrt{\frac{1}{9}(1.841)}$ = 0.453

Bias = $\frac{1}{9}(1.09)$ = 0.121

d = $1 - \frac{(1.841)}{19.79}$ = 0.907

SB = $(4.43\text{-}4.31)^2$ = 0.0144

TableAIII-4: Computation of values of t statistic for inference on slope and intercept hypotheses (Grain Damage)

Measured	Predicted	x deviates	y deviates	Square x deviates	Square y deviates	Product xy deviates
x	y	x-$\bar{x}$	y-$\bar{y}$	x^2	y^2	xy
4.83	4.75	0.1400	-0.0100	0.0196	0.0001	-0.0014

5.12	5.38	-0.2500	-0.0900	0.0625	0.0081	0.0225
5.70	5.99	1.1800	1.2400	1.3924	1.5376	1.4632
4.11	4.20	0.7400	0.5800	0.5476	0.3364	0.4292
3.15	3.74	0.9800	1.3200	0.9604	1.7424	1.2936
4.38	4.41	-0.1100	0.0100	0.0121	0.0001	-0.0011
3.85	4.08	-1.1700	-1.4100	1.3689	1.9881	1.6497
3.69	3.66	1.5500	1.0800	2.4025	1.1664	1.6740
3.98	3.69	-1.0900	-1.4300	1.1881	2.0449	1.5587
$\bar{x} = 4.31$	$\bar{y}$ =4.43			$\boldsymbol{\Sigma}$=4.955	$\boldsymbol{\Sigma}$=5.683	$\boldsymbol{\Sigma}$=4.832

$$S^2{}_{y.x} = \frac{\sum y^2 - \frac{(\sum xy)^2}{\sum x^2}}{n-2} = 0.673$$

$$t_b = \frac{b}{\sqrt{\frac{S^2{}_{y.x}}{\sum x^2}}} = 2.064$$

$$t_\alpha = \frac{\alpha - \alpha_0}{\sqrt{S^2{}_{y.x}\left(\frac{1}{n} + \frac{\bar{x}^2}{\sum x^2}\right)}} = 0.140$$

Appendix III: Computation of Model performance Evaluation Parameters

Grain Loss

Table AIII-5: Computation of *RMSE, Bias, SB* and *d*

Measured	Predicted					A	B	
M	P	P-M	$(P-M)^2$	$P-\bar{M}$	$O-\bar{M}$	$\lvert P-\bar{M}\rvert$	$\lvert O-\bar{M}\rvert$	$(A+B)^2$

14.32	14.18	-0.14	0.0196	-0.66	-0.52	0.66	0.52	1.3924
15.47	14.95	-0.52	0.2704	0.11	0.63	0.11	0.63	0.5476
16.56	15.83	-0.73	0.5329	0.99	1.72	0.99	1.72	7.3441
13.88	13.13	-0.75	0.5625	-1.71	-0.96	1.71	0.96	7.1289
15.27	13.98	-1.29	1.6641	-0.86	0.43	0.86	0.43	1.6641
14.94	12.41	-1.92	3.6864	-2.43	0.10	2.43	0.10	6.4009
15.50	13.90	-1.60	2.5600	-0.94	0.66	0.94	0.66	2.5600
14.29	12.36	-1.93	3.7249	-2.48	-0.55	2.48	0.55	9.1809
13.34	11.47	-1.87	3.4969	-3.37	-1.50	3.37	1.50	23.7169
$\bar{M}$ =14.84	$\bar{P}$=13.58	-11.36	Σ=19.23				Σ =7.05	Σ=59.93

RMSE = $\sqrt{\frac{1}{9}(19.23)}$ = 1.462

Bias = $\frac{1}{9}(-11.36)$ = -1.262

d = $1 - \frac{19.23}{59.93}$ = 0.679 (NB: correlation is significant (r table = 0.666 at df = 7, 5 % significance)

SB= $(13.58-14.84)^2$ = 1.587

Table AIII-6: Computation of values of t statistic for inference on slope and intercept hypotheses (Grain Loss)

Measured	Predicted	x deviates	y deviates	Square x deviates	Square y deviates	Product xy deviates

x	y	x-$\bar{x}$	y-$\bar{y}$	x^2	y^2	xy
14.32	14.18	-0.6500	0.4000	0.4225	0.1600	-0.2600
15.47	14.95	0.5000	1.1700	0.2500	1.3689	0.5850
16.56	15.83	1.5900	2.0500	2.5281	4.2025	3.2595
13.88	13.13	-1.0900	-0.6500	1.1881	0.4225	0.7085
15.27	13.98	0.3000	0.2000	0.0900	0.0400	0.0600
14.94	12.41	1.1300	0.4000	1.2769	0.1600	0.4520
15.50	13.90	0.5300	0.1200	0.2809	0.0144	0.0636
14.29	12.36	-0.6800	-1.4200	0.4624	2.0164	0.9656
13.34	11.47	-1.6300	-2.3100	2.6569	5.3361	3.7653
$\bar{x} = 14.84$	$\bar{y}$ =13.58			$\boldsymbol{\Sigma}$=7.730	$\boldsymbol{\Sigma}$=15.074	$\boldsymbol{\Sigma}$= 8.955

$$S^2{}_{y.x} = \frac{\sum y^2 - \frac{(\sum xy)^2}{\sum x^2}}{n-2} = 1.988$$

$$t_b = \frac{b}{\sqrt{\frac{S^2{}_{y.x}}{\sum x^2}}} = 2.028$$

$$t_\alpha = \frac{\alpha - \alpha_0}{\sqrt{S^2{}_{y.x}\left(\frac{1}{n} + \frac{\bar{x}^2}{\sum x^2}\right)}} = 0.478$$

Appendix IV: Sensitivity Analyses

Shelling Efficiency sensitivity coefficients

$\lambda_S = 0.0385\ C^{0.73} \left(\frac{\rho V}{F}\right)^{0.52} \left(\frac{1}{DM}\right)^{0.69}$

$N_s = (1 - e^{-\lambda_S l})$ x 100 %

Let $k_\rho = 0.0385\ LC^{0.73} \left(\frac{V}{F}\right)^{0.52} \left(\frac{1}{DM}\right)^{0.69}$

Then, $N_s = (1 - e^{-k_\rho \rho^{0.52}})$ x 100 %

Therefore, $\frac{\partial Ns}{\partial \rho} = 52\rho^{-0.48} k_\rho e^{-k_\rho \rho^{0.52}}$

Similarly, let $k_v = 0.0385\ LC^{0.73} \left(\frac{\rho}{F}\right)^{0.52} \left(\frac{1}{DM}\right)^{0.69}$

then, $N_s = (1 - e^{-k_v v^{0.52}})$ x 100 %

Therefore, $\frac{\partial Ns}{\partial v} = 52v^{-0.48} k_v e^{-k_v v^{0.52}}$

Also,

Let, $k_c = 0.0385\ L \left(\frac{\rho V}{F}\right)^{0.52} \left(\frac{1}{DM}\right)^{0.69}$

Then, $N_s = (1 - e^{-k_c c^{0.73}})$ x 100 %

Therefore, $\frac{\partial Ns}{\partial c} = 73c^{-0.27} k_\rho e^{-k_c c^{0.73}}$

Again, if $k_f = 0.0385\ LC^{0.73} (\rho V)^{0.52} \left(\frac{1}{DM}\right)^{0.69}$

Then, $N_s = (1 - e^{-k_f \left(\frac{1}{F}\right)^{0.52}})$ x 100 % ; $N_s = (1 - e^{-k_f (F)^{-0.52}})$ x 100 %

Therefore, $\frac{\partial Ns}{\partial f} = -52 k_f\ (F)^{-1.52} e^{-k_f (F)^{-0.52}}$

if $k_D = 0.0385 LC^{0.73} \left(\frac{\rho V}{F}\right)^{0.52} \left(\frac{1}{M}\right)^{0.69}$

Then, $N_s = (1 - e^{-k_D \left(\frac{1}{D}\right)^{0.69}})$ x 100 %

Therefore, $\frac{\partial Ns}{\partial D} = -69 k_D\ (D)^{-1.69} e^{-k_D (D)^{-0.69}}$

Let $k_M = 0.0385LC^{0.73}\left(\frac{\rho V}{F}\right)^{0.52}\left(\frac{1}{D}\right)^{0.69}$

Then, $N_s = (1 - e^{-k_M\left(\frac{1}{M}\right)^{0.69}})$ x 100 %

Therefore, $\frac{\partial Ns}{\partial M}$ = -69$k_M\ (M)^{-1.69}e^{-k_M\left(\frac{1}{M}\right)^{0.69}}$

$\lambda_S = 0.0385\ C^{0.73}\left(\frac{\rho V}{F}\right)^{0.52}\left(\frac{1}{DM}\right)^{0.69}$ =5.00116,

$N = (1 - e^{-\lambda_S l})$ x 100 % = 96.58 %

$\frac{\partial \mathrm{N}}{\partial \rho}$ = 0.002313 $N\xi = (\frac{\partial N}{\partial u_1}.\frac{u_1}{N})u_1\xi$ Nξ =0.002313 x 800/96.58 =0.0196162

Similarly,

$\frac{\partial \mathrm{N}}{\partial v}$ = 0.264379241 Nξ =0.264379241x 7/96.58 = 0.019162

$\frac{\partial \mathrm{N}}{\partial c}$ = 74.22955616 Nξ = 74.22955616 x 0.035/96.58 = 0.0269

$\frac{\partial \mathrm{N}}{\partial f}$ = --3.70130938 Nξ = --3.70130938 x 0.50/96.58 = -0.01916

$\frac{\partial \mathrm{N}}{\partial D}$ = -13.6426467 Nξ = -13.6426467 x 0.18/96.58 = -0.02543

$\frac{\partial \mathrm{N}}{\partial M}$ = -27.2852935 Nξ = -27.2852935 x 0.09/ 96.58 = -0.02543

Appendix IV: Sensitivity Analyses (contd)

Grain damage sensitivity coefficients

$\lambda_D = 1.15E-04\ C^{1.68}\left(\frac{\rho V}{F}\right)^{0.95}\left(\frac{1}{DM}\right)^{0.78}$

$N_{d=}(1-e^{-\lambda_D l})$ x 100 %

Let $k_\rho = 1.15E-04\ LC^{1.68}\left(\frac{V}{F}\right)^{0.95}\left(\frac{1}{DM}\right)^{0.78}$

Then, $N_{s=}(1-e^{-k_\rho \rho^{0.95}})$ x 100 %

Therefore, $\frac{\partial Ns}{\partial \rho} = 95\rho^{-0.05}k_\rho e^{-k_\rho \rho^{0.95}}$

Similarly, let $k_v = 1.15E-04\ LC^{0.73}\left(\frac{\rho}{F}\right)^{0.95}\left(\frac{1}{DM}\right)^{0.78}$

then, $N_{D=}(1-e^{-k_v v^{0.95}})$ x 100 %

Therefore, $\frac{\partial ND}{\partial v} = 95v^{-0.05}k_v e^{-k_v v^{0.95}}$

Also,

Let, $k_c = 1.15E-04L\left(\frac{\rho V}{F}\right)^{0.95}\left(\frac{1}{DM}\right)^{078}$

Then, $N_{D=}(1-e^{-k_c c^{1.68}})$ x 100 %

Therefore, $\frac{\partial ND}{\partial c} = 168c^{0.68}k_c e^{-k_c c^{1.68}}$

Again, if $k_f = 1.15E-04\ LC^{1.68}(\rho V)^{0.95}\left(\frac{1}{DM}\right)^{0.78}$

Then, $N_{D=}(1-e^{-k_f\left(\frac{1}{F}\right)^{0.95}})$ x 100 % ; $N_{D=}(1-e^{-k_f(F)^{-0.95}})$ x 100 %

Therefore, $\frac{\partial ND}{\partial f}$ = -. - -$95k_f\ (F)^{-1.95}e^{-k_f(F)^{-0.95}}$

if $k_D = 1.15E-04LC^{1.68}\left(\frac{\rho V}{F}\right)^{0.95}\left(\frac{1}{M}\right)^{0.78}$

Then, $N_{D=}(1-e^{-k_D\left(\frac{1}{D}\right)^{0.78}})$ x 100 %

Therefore, $\frac{\partial ND}{\partial D}$ = -78$k_D\,(D)^{-1.78}e^{-k_D(D)^{-0.78}}$

Let $k_M = 1.15E-04LC^{1.68}\left(\frac{\rho V}{F}\right)^{0.95}\left(\frac{1}{D}\right)^{0.78}$

Then, $N_{D=}(1-e^{-k_M\left(\frac{1}{M}\right)^{0.78}})$ x 100 %

Therefore, $\frac{\partial ND}{\partial M}$ = -78$k_M\,(M)^{-1.78}e^{-k_M\left(\frac{1}{M}\right)^{0.78}}$

$\lambda_D = 1.15E-04\,C^{1.68}\left(\frac{\rho V}{F}\right)^{0.95}\left(\frac{1}{DM}\right)^{0.78}$ = 0.04145

$N=(1-e^{-\lambda_D l})$ x 100 % = 2.76

$\frac{\partial \mathrm{N}}{\partial \rho}$ = 0.0005506

$$N\xi = (\frac{\partial N}{\partial u_1}.\frac{u_1}{N})u_1\xi$$

Nξ =0.005506x 800/2.76 =0.15960

Similarly,

$\frac{\partial \mathrm{N}}{\partial V}$ = 0.062930 Nξ =0.06293 x 7/2.76 = 0. 15960

$\frac{\partial \mathrm{N}}{\partial C}$ = 0.836703 Nξ = 0.836703 x 0.035/2.76 = 0.010610

$\frac{\partial \mathrm{N}}{\partial F}$ = -0.88101 Nξ = -0.88101x 0.50/2.76 = -0.15960

$\frac{\partial \mathrm{N}}{\partial D}$ = -2.0093286 Nξ = -2.0093286 x 0.18/2.76 = -0.13104

$\frac{\partial \mathrm{N}}{\partial M}$ = -4.018657 Nξ = -4.018657 x 0.09/ 2.76 = -0.13104

Appendix V: MATLAB Optimization Program

Equal Weighing Vectors

```
% A matlab optimization program to find the optimal speed (S),
% Feed rate (F), Moisture content (M) and Concave Clearance (C) for IAR
%Maize Dehusker Sheller
%function Optimize (Fitness Function)
%Declare matrices S,F, M, C
FitnessFunction = @sw_eval_func;
global S F M C

%initialize matrices S, F, M, C

[S F M C]= ndgrid(750:100:950,30:10:50,9:3:15,35:5:45);

 %load machine performance output parameters i.e Shelling efficiency (Y1),
  Grain Damage(Y2) and Scatter loss(Y3)

%set matlab genetic algorithm options

options = gaoptimset('PlotFcns',
{@gaplotbestf,@gaplotbestindiv,@gaplotscores,@gaplotdistance}, ...
'PopulationSize',100,'SelectionFcn',@selectionroulette,'MutationFcn',@mutationadaptfea
sible,...
'Generations',100);

%start Optimization
[x,Fval,exitFlag,Output] = gamultiobj(FitnessFunction,4,[],[],[],[],[750 30 9 35],[950 50 15
45],options);

SE = interp2(S,F,M,C,Y1,x(1,1),x(1,2),x(1,3),x(1,4));
DG = interp2(S,F,M,C,Y2,x(1,1),x(1,2),x(1,3),x(1,4));
SC = interp2(S,F,M,C,Y3,x(1,1),x(1,2),x(1,3),x(1,4));

%print output
fprintf('The number of generations was : %d\n', Output.generations);
fprintf('\nOptimal machine input are as follows:\n');
fprintf('Speed(S) : %f\n', x(1,1));
fprintf('Feed Rate(F) : %f\n', x(1,2));
fprintf('Moisture Content(M) : %f\n', x(1,3));
fprintf('Concave clearance(C) : %f\n', x(1,4));
fprintf('\nMachine output at optimal input is as follows:\n');
fprintf('Shelling Efficiency : %f\n', interp2(S,F,M,C,Y1,x(1,1),x(1,2),x(1,3),x(1,4)));
```

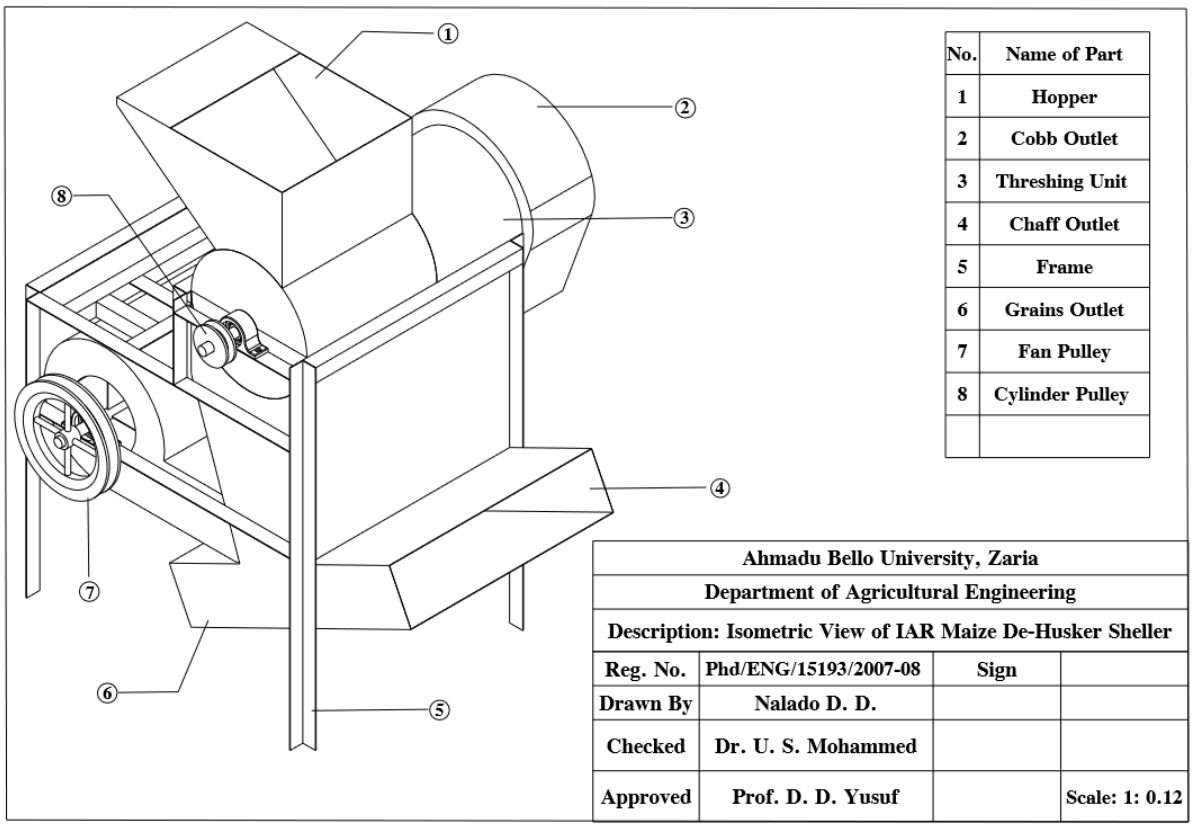
```
fprintf('Grain Damage : %f\n', interp2(S,F,M,C,Y2,x(1,1),x(1,2),x(1,3),x(1,4)));
fprintf('Scatter Loss : %f\n', interp2(S,F,M,C,Y3,x(1,1),x(1,2),x(1,3),x(1,4)));
function y=funname(x)
%combination of all functions
% equal weighing vectors
w1 = 1/3;
w2 = 1/3;
w3 = 1/3;

lamda_s= 0.0385*(((x(1)*x(3))/x(2))^0.52)*((inv(x(4)*x(7)))^0.69)*x(5)^0.73;
y1=-(1-exp(-lamda_s*x(6)))*100;
%maximize the shelling efficiency

lamda_d= 0.000115*(((x(1)*x(3))/x(2))^0.95)*((inv(x(4)*x(7)))^0.78)*x(5)^1.68;
y2=(1-exp(-lamda_d*x(6)))*100;
% minimize grain_damage

lamda_s= 0.0385*(((x(1)*x(3))/x(2))^0.52)*((inv(x(4)*x(7)))^0.69)*x(5)^0.73;
betta=0.81*((x(2)/(x(1)*x(3)))^0.48)*((inv(x(5)))^2.69)*(x(4)*x(7))^0.33;
y3=(lamda_s/(lamda_s-betta))*(exp(-betta*x(6))-exp(-lamda_s*x(6)));
%minimize grain_loss

y = y1*w1 + y2*w2 + y3*w3;
```

Selective Weighing vectors

```
% A matlab optimization program to find the optimal speed (S),
% Feed rate (F), Moisture content (M) and Concave Clearance (C) for IAR
%Maize Dehusker Sheller
%function Optimize (Fitness Function)
%Declare matrices S,F, M, C
Fitness Function = @sw_eval_func;
global S F M C

%initialize matrices S, F, M, C

[S F M C]= ndgrid(750:100:950,30:10:50,9:3:15,35:5:45);

 %load machine performance output parameters i.e Shelling efficiency (Y1),
  Grain Damage (Y2) and Scatter loss(Y3)

%set matlab genetic algorithm options

options = gaoptimset('PlotFcns',
{@gaplotbestf,@gaplotbestindiv,@gaplotscores,@gaplotdistance}, ...
'PopulationSize',100,'SelectionFcn',@selectionroulette,'MutationFcn',@mutationadaptfea
sible,...
'Generations',100);

%start Optimization
[x,Fval,exitFlag,Output] = gamultiobj(FitnessFunction,4,[],[],[],[],[750 30 9 35],[950 50 15
45],options);

SE = interp2(S,F,M,C,Y1,x(1,1),x(1,2),x(1,3),x(1,4));
DG = interp2(S,F,M,C,Y2,x(1,1),x(1,2),x(1,3),x(1,4));
SC = interp2(S,F,M,C,Y3,x(1,1),x(1,2),x(1,3),x(1,4));

%print output
fprintf('The number of generations was : %d\n', Output.generations);
fprintf('\nOptimal machine input are as follows:\n');
fprintf('Speed(S) : %f\n', x(1,1));
fprintf('Feed Rate(F) : %f\n', x(1,2));
fprintf('Moisture Content(M) : %f\n', x(1,3));
```

```
fprintf('Concave clearance(C) : %f\n', x(1,4));
fprintf('\nMachine output at optimal input is as follows:\n');
fprintf('Shelling Efficiency : %f\n', interp2(S,F,M,C,Y1,x(1,1),x(1,2),x(1,3),x(1,4)));
fprintf('Grain Damage : %f\n', interp2(S,F,M,C,Y2,x(1,1),x(1,2),x(1,3),x(1,4)));
fprintf('Scatter Loss : %f\n', interp2(S,F,M,C,Y3,x(1,1),x(1,2),x(1,3),x(1,4)));
function y=funname(x)
%combination of all functions
% selective weighing vectors
w1 = 2/9
w2 = 4/9;
w3 = 3/9;

lamda_s= 0.0385*(((x(1)*x(3))/x(2))^0.52)*((inv(x(4)*x(7)))^0.69)*x(5)^0.73;
y1=-(1-exp(-lamda_s*x(6)))*100;
%maximize the shelling efficiency

lamda_d= 0.000115*(((x(1)*x(3))/x(2))^0.95)*((inv(x(4)*x(7)))^0.78)*x(5)^1.68;
y2=(1-exp(-lamda_d*x(6)))*100;
% minimize grain_damage

lamda_s= 0.0385*(((x(1)*x(3))/x(2))^0.52)*((inv(x(4)*x(7)))^0.69)*x(5)^0.73;
betta=0.81*((x(2)/(x(1)*x(3)))^0.48)*((inv(x(5)))^2.29)*(x(4)*x(7))^0.33;
y3=(lamda_s/(lamda_s-betta))*(exp(-betta*x(6))-exp(-lamda_s*x(6)));
%minimize grain_loss

y = y1*w1 + y2*w2 + y3*w3;
```

Appendix VI: DRAWINGS



No.	Name of Part
1	Hopper
2	Cobb Outlet
3	Threshing Unit
4	Chaff Outlet
5	Frame
6	Grains Outlet
7	Fan Pulley
8	Cylinder Pulley

Ahmadu Bello University, Zaria			
Department of Agricultural Engineering			
Description: Isometric View of IAR Maize De-Husker Sheller			
Reg. No.	Phd/ENG/15193/2007-08	Sign	
Drawn By	Nalado D. D.		
Checked	Dr. U. S. Mohammed		
Approved	Prof. D. D. Yusuf		Scale: 1: 0.12

Fig AVI-1: Isometric view of IAR Maize Dehusker Sheller

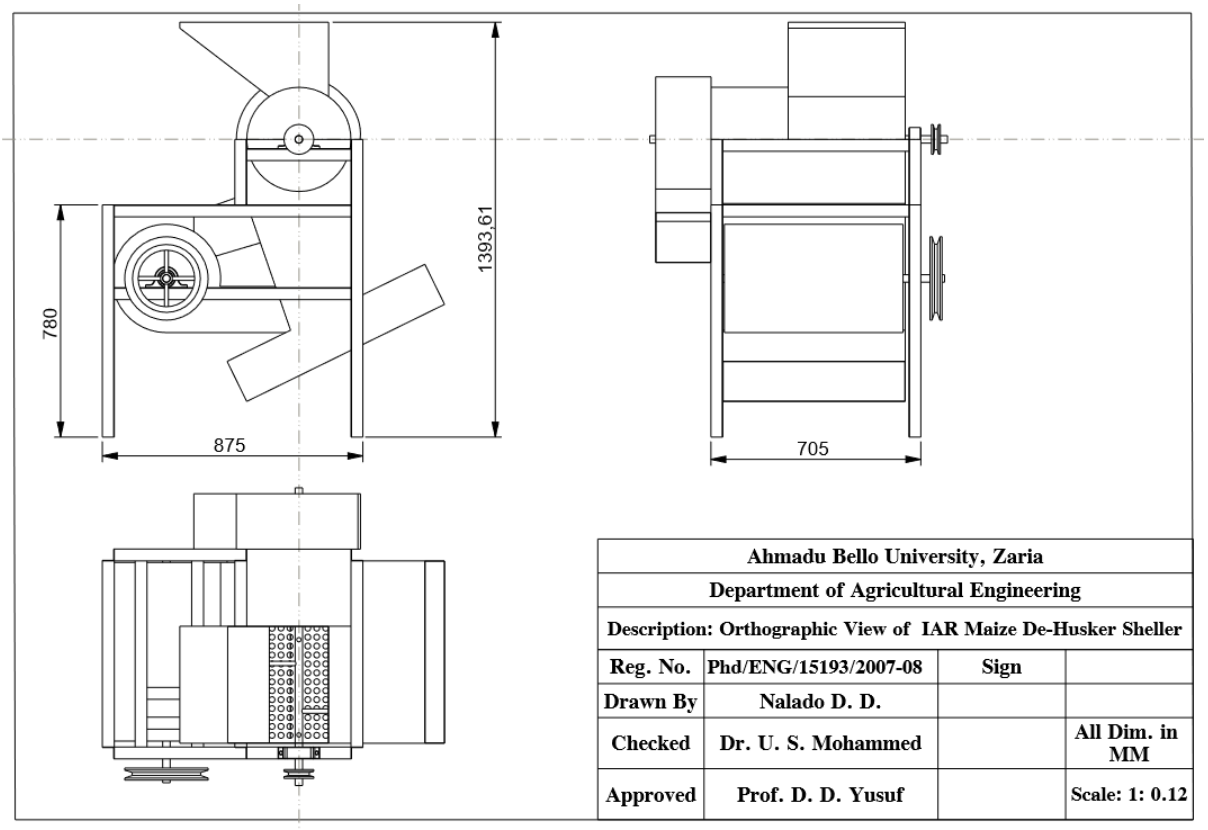


Fig AVI-2: Orthographic Drawing of IAR Maize Dehusker Sheller