IJSCIA
International Journal of Scientific Advances
ISSN: 2708-7972
Volume: 6 | Issue: 4 | Jul – Aug 2025 Available Online: www.ijscia.com
DOI: 10.51542/ijscia.v6i4.4

Farm Machinery Cost and Size Management and Optimization for Wheat Production in Dongola Area, Northern State, Sudan

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ABSTRACT

Machinery management has increased in importance in recent farming operations because of its direct relation to the success of mixing inputs to return a satisfactory profit. The study aimed to develop a computer system to be used as a decision-making tool for improving the efficiency of field operations mechanization (land preparation, planting and harvesting) management for wheat production under Northern state, Dongola area. The data collected included machine purchase prices (SDG), expected working days, working hours per day, repair and maintenance (R&M) costs as (%) of purchase prices according to annual hours of use, machine age (years), area to be covered (ha), machine rent per hour (SDG), labor wage per hour, fuel unit price (SDG/L) and required tractor power (KW). The data were used to run the computer program and to compare the system predictions with the actual field data. The developed program contained two units namely; Machinery performance unit to estimate effective field capacity (ha/h), and unit for field operations costs in (SDG/h and SDG/ ha). Principles of operation research (OR) and linear programming (LP) mathematical modeling techniques were employed to formulate the main objective functions and optimization. T-test was used to analyze the collected data. The results showed strong positive correlation between predicted and actual field capacity (R2 = 0.963). For land preparation, actual field capacity was significantly ($P \le 0.05$) higher (2.1ha/h) than the predicted one (1.71ha/h), while for the planting operation, the predicted effective field capacity of BALDAN drill was higher by 28% than the actual field capacity. On the other hand, the predicted field capacity of FOTTON harvesting machine was higher by 19% than the actual. Moreover, for land preparation operation cost, the system predicted the lowest total operation costs (155038.9 SDG) for offset disc harrow (2.70m) compared to the actual total operation costs while for the planting operations costs, Agro-master drill gave the lowest predicted total operation cost (171353.52 SDG) compared the actual total operation costs. Furthermore, FOTTON 4Lz2 recorded lower predicted harvesting operation cost (174841.3 SDG) compared to the actual operation cost. After optimization it was found that, the best combination options, for land preparation it was 21 tillage implements of size 1.9 m with 34 implements, size 3.65 m, while for planting operation it was four implements, size 3.30m, with 36 implements, size 4.00m and for harvesting operation it was two combine harvesters, size 4.20m with 43 combine harvester of size 4.30m to cover the 50000 ha field area. It was concluded that the developed program is valid to estimate these parameters with a high level of confidence and accuracy.

Keywords: computer Program; management; combine harvester; planters; implements; optimization.

INTRODUCTION

The necessity of agricultural production is increasing day by day to face the rapidly increasing world population. The total cropped area throughout the world is increasing and the labor employed in farming is decreasing and the needs to use farm tractors and machineries are increased (Aryal *et al.*, 2019), The ultimate goal of the machinery manager is to maximize enterprise profits by getting the greatest output from machines at a minimum cost (Hunt, 2015). The degree of mechanization should be decided by the producer (farmer) to best suit his business and his own circumstances (Clarke, 2000).

The total time required for machine operation depends on the capacity of the machine, the number of available working days, and the number of available working hours of use (Siemens *et al.*, 1999). The measure of timeliness is the cost incurred because the operation was not completed in the optimum period. Accurate estimation of machinery cost plays an important role in every machinery management decision (Lazarus and Selley, 2005; Edwards and George, 2008). Selecting a tractor with considerably more power than necessary can cause poor implement performance if excess speed is used and cause excessive wear and damage under adverse soil conditions (Dahab and Mergani, 2021).

On the other hand, using a tractor with less power than required can limit field capacity, causing untimely operation, excessive wheel slippage and tire wear, and provide poor soil pulverization and cause tractor failure because of continuous overload (FMO, 1987). Investing in larger machinery can reduce the variability of net machinery costs by ensuring that crops are planted and harvested on time, even in years in which there are few workdays, but with proper management. Machinery management has increased in importance in recent farming operations because of its direct relation to the success of mixing land, labor, and capital to return a satisfactory profit. Optimum farm machinery management occurs when the economic performance of the total machine system has been maximized. A successful business farm is obtained when machinery is considered as only tools of production and operated in a business-like manner to produce crops at a profit (Hunt, 2015). A mathematical model is made of all sorts of mathematical objects: variables, constants, functions, equations, and symbols. The investigation of such a model and possible application of it will often involve the use of computers and other data processing equipment (Bol *et al.*, 2006). Mathematical models are used to develop computer systems and procedures.

The main concern is that the system performs to the highest level we can achieve within the data or information at hand, and the developed system should be a well-defined products, which meet the standards of the users (David, 2004). Computer software packages increasingly become acceptable and adopted as tools for farm management and decision-making (Mohammed, 2006; Yousif, 2011; Dahab *et al*, 2024). Computer-based models are now used to analyze and optimize agricultural machinery systems. Many computer models were developed to analyze the factors affecting machinery performance and selection, field operations, and total farm costs (Ismail, 1998; Alam *et al*, 2001). A linear program is a mathematical formulation of a problem. It refers to a planning process that allocates resources (machines, labor, capital, materials, and time) in the best possible (optimal) way, so that the costs are minimized or profit maximized. In a linear program (LP), the decision variables must be continuous, and the objective functions and constraints must be linear in expression (Sowell and Ward 1998). The agricultural sector has an important role to play in achieving food Security by increasing food production and providing employment opportunities in the rural areas (Strauss, 2005). In Sudan, the agriculture sector is important; it supplies food for the people, employment opportunities, and provides the industrial sector with raw materials. Sudan is considered one of the three countries in the world that can contribute to international food security (FAO, 2015). Pre-secession, Sudan had cultivable arable land estimated at 86 million hectares. Post-secession, it has been diminished by about 30% of the total. However, less than 20% are utilized under three major farming sub-sectors: the irrigated, the semi-mechanized rainfed, and the traditional rain-fed (Abdalla and Abdel Nour, 2004; Shambat *et al.*, 2017).

In northern Sudan, wheat production is affected by some limiting factors such as high cost of production, low crop productivity, and high input costs, including prices of machinery spare parts (Dahab and Mahgoub, 2009). There is a continuous need for advanced machinery to meet higher production requirements and the full utilization of production resources. Optimization of farm machinery is a complex problem and faces both individual farmers and other enterprise managers in the Dongola area. There is a need to determine the most optimal machine type, size, and capacity that satisfy the required field operations (Dahab *et al.*, 2023; Dahab *et al.*, 2024; Dahab *et al.*, 2025). This can be solved by accurate estimation of total working time that is available for major field operations, determine the required effective field capacity of machines, match power unit to machines and predict costs accurately for any machine application by using computer programs and software (Dahab *et al.*, 2018, Dahab *et al.*, 2024).

The important and major field operations of the wheat crop are land preparation, planting, and harvesting; thus, these operations must receive more consideration and management to increase the crop production and productivity. Therefore, the main objective of this study is to develop a machinery management system for wheat production by using computer programming, to estimate the effective field capacity (EFC) and operation costs for different machines used and also employment of operation research (OR) and using linear programing (LP), simplex method as mathematical modeling technique based on algebraic solution analysis, for optimization sizes and costs of farm machinery. Validation, sensitivity, and accuracy tests will be carried out for the developed computer system.

2. MATERIALS AND METHODS

2.1 Location

The Northern State lies between latitudes 16^{0}-22^{0} N and longitudes 20^{o}-32^{o} E. The State lies in the arid and semi-arid zones, where the annual rainfall is less than 100 mm. There are two distinct seasons, winter, which extends from October to the end of March, where large areas are cultivated by food and cash crops, and the summer season extends from April to the end of September, where limited areas are cultivated. The total area of the Northern State is about 85.5 million feddan, about 5% out of which is suitable for agricultural production. However, this agricultural area is not fully utilized (AOAD, 1995). The soil of Northern State is divided into two main groups, namely the soil of the recent flood plain, which includes the Garif and Gorier soils, besides the basin and the soil of the upper terrace soils which is classified as saline sodic soil. The planned area to be cultivated by wheat in the study area (Dongola, Algoid, and Eldaba localities) is 120000 feddan (50000 hectares) for most seasons under upper terraces soils (MAAW, 2017).

2.2 Types of data required

The required input data to run the system was collected from literature and many different concerned resources such as the Ministry of Agriculture and Animal Wealth (MAAW), Agricultural Research Station, Alshamalia company for agricultural machinery services, Agricultural Bank of Sudan (Dongola branch), and Agricultural machinery dealers. Also, some data were collected through direct interviews of agricultural engineers, operators, and farm managers. The collected data included types and sizes of machines, field efficiency, machine speed, purchase price, purchase date, width of machine, and the number of machines used in each operation and start and end of each operation and working hours per day, and hours of use of machines.

2.3 Types of machinery used

Different types, makes, models, and power sizes of tractors and machinery are used to carry out the different field operations. Combine harvesters of different makes. Sizes and models are used for the harvesting operation.

2.4 Computer system requirements:

(1) Personal computer, TOSHIBA, processor Intel CORE i3, RAM 4 Gigabytes, Windows 10 (32 bit), Hard Disc (HD) 500 Gigabytes.

(2) Installation of Microsoft Office packages software, which includes Excel 2010, Linear programming (LP) software (simplex method).

(3) The program is pre-loaded with the published data and information of standard machinery technical parameters and equations adopted by ASAE (2000), Hunt (2008), Witney (1988), Siemens *et al.*, (1998)

(4) The system employs International System (SI) metric units.

2.5 The computer system development and description

The system is composed of two sections:

Section one: This section contains two units: -

(1) Machinery performance unit: It is used to calculate the effective field capacity (EFC) in (ha/hr) for different machines used in the selected operations.

(2) Field operations cost unit: In this unit fixed cost (FC) and variable cost (VC) for different tractors power, implements and combine harvesters used in each of the selected operation can be calculated and consequently field operation cost per hour (SDG/hr) and operation cost (SDG/ ha) can be estimated.

Section two: output reports of machine capacity (EFC, ha/hr) and field operation cost (SDG/hr), used as inputs in this section. Through employing operation research (OR) using linear programing (LP) software and applying simplex method, with consideration of machine effective field capacity (ha/hr) as objective function coefficients, (machine numbers, working hours/ day and operation cost per hour) as decision variables coefficients and (total machine numbers, total operation cost per hour according to the assumed budget and annual hours of use) as constraints (available resources) for the three operations land preparation, planting and harvesting. This case is considered a linear programming production problem (maximization) that can be solved by the application of the simplex method maximization technique.

2.6 System technical specifications

The developed system's technical specifications are shown in Table 1.

TABLE 1: System Technical Specifications.

Item	System	(LP)Software (Tora)
System language	Cake PHP framework	Excel
System type	Button menu-driven	Button menu-driven and S. sheet
System dependability	Windows 7	Windows 7
System interface	Main menu	Spread sheet
Units used	SI units	SI units

2.7 System features

The system is button menu-driven and composed of two sections. Section one contains two units: the machinery performance estimation unit and the field operation costs estimation unit. The user's input data is displayed directly on the screen.

All units in section one is built up in Excel and in a separate program file. The user has the choice to perform each unit separately. Data entry is by step-by-step process in a specially designed interface for each unit.

The user has the option to use the data stored in the program files or enter their own data. Data input may be corrected directly from the screen display. The option may be the machinery list menu, the tractors list menu, the harvesters list menu, or the field operations cost list menu. The program is pre-loaded with the parameters and equations adopted by ASAE (2000), Hunt (2008), Siemens *et al* (1998), and Dahab (2000). The equations used to compute machine capacities (EFC) in (ha/hr), and estimation of operations costs based on International Units (SI) and Sudanese currency (SDG) in SDG/hr. The system output can be displayed on the screen or saved, or printed out. The expected reports include machine effective field capacity (ha/hr), tractors and harvesters fixed cost (FC) and variable cost(VC) per hour in (SDG/hr), machine fixed cost(FC) and variable cost(VC) per hour in (SDG)/hr), operations fixed (FC) and variable cost(VC) per hour in (SDG/hr), operation total cost per hour in (SDG/hr) and operation cost per hectare (SDG/ ha). In section two through generating linear programing, production problem (maximization) from the output of the system, (machine capacity (EFC) (ha/h) of the selected machines (decision variables) to formulate the objective function with consideration to operation cost per hour (SDG/h) and available working hours per day as decision variables coefficients, and the assumed constraints, budget per hour, total numbers of available machines and annual hours of use. Through applying linear programming (LP) software (Tora), linear and integer programming, and using of simplex method technique as a decision-making aid tool to obtain the optimization of machine sizes and cost in land preparation, planting, and harvesting operations.

2.8 Program data files

a. Tractors file

The file contains a list of different types of tractors that may be used in land preparation, planting, and harvesting operations. The file contains information including tractor make, tractor engine power (KW), PTO power, purchase price, purchase date, and life span. The information in the file may be changed by the program user and stored.

b. Implements file

It contains a list of different implements that may be used to perform land preparation, planting, and harvesting operations. The information in the file includes machine name, size (width), working speed, estimated field efficiency, and power required. The information in the file may be changed by the program user and stored.

c. Field operations file

The most important information input by the user is the list of desired field operations to be achieved and the related to these operations. One of the program objectives is to select the required machinery to complete the desired field operations in the optimum period and with the least cost. The file contains a list of the desired field operations (land preparation, planting, and harvesting). The data include operation name, location, tractors used, implement used, start and end dates of the operation, available working days, available working hours/day, and fuel price. Matching implements and tractors is done according to implement size and power requirements.

2.9 Machinery performance data

The required input data values for farm tractors and machines used to calculate effective field capacity (ha/hr) and fuel consumption (L/hr) are as follows:

(1) Tractors and machine names,
(2) Machine width (m),
(3) Tractor engine power (KW),
(4) Tractor's power takes off shaft power (PTO) (KW),
(5) Machine working speed (km/hr).
(6) Assumed field efficiency (%),
(7) Fuel consumption rate in liters per hectare (L/ha).

2.9.1 Machine capacity equation: Based on the equation given by ASAE (2000), Witney (1988), Siemens *et al* (1999).

Effective field capacity (EFC) = SWE /C

Where:

EFC =Effective field capacity (ha /hr).
S= Machine working speed (km /h). W =Machine width (m).
E= Field efficiency (%). C= Constant= 10

2.9.2 Farm operation costs estimations:

Calculation of costs depends on mathematical equations adopted by ASAE (2000), Siemens *et al.,* (1998), and Hunt (2008).

The costs included the following:

- Fixed costs are calculated as Depreciation (D), Taxes (T), Shelter (S), Insurance (I), and Return on investment (ROI).
- Variable costs vary with machine use and include repair and maintenance costs (R&M), fuel cost, oil cost, and labor cost.

2.9.3 Land preparation and planting operations costs:

Field operation cost per hour is the summation of tractor fixed cost (TFC) /hour + tractor variable cost (TVC)/ hour + implement fixed cost (Imp FC)/ hour + implement variable cost (Imp VC /hour.

Operation Fixed cost /hour = TFC +ImpFC SDG/hr

Operation Variable cost /hour = TVC+ Imp VC SDG/hr

Operation cost / hr = Operation Fixed cost /hr +

Operation Variable cost /hr. (SDG/hr.)

Operation cost per hectare (SDG/ha)

$$= \frac{Operation\frac{cost}{hr}\left(\frac{SDG}{hr}\right)}{Machine\ capacity(EFC)\frac{ha}{hr}}$$ Operation cost / hr (SDG/hr) ÷ machine capacity (EFC) (ha/hr.) (SDG/ha).

2.9.4 Combine Harvesting Operation Cost:

Harvesting Operation Fixed cost /hour
= HFC/Annual use SDG/hr

Harvesting Operation Variable cost /hour
= HVC/ Annual use (SDG/hr)

Harvesting Operation cost/hr
= Operation Fixed cost /hr + Operation Variable cost /hr. (SDG/hr.)

Operation cost per hectare (SDG/ha)

$$= \frac{Operation\ cost/hr\ (\frac{SDG}{hr})}{Machine\ capacity(EFC)\ ha/hr}$$

Operation cost / hr. (SDG/hr.) ÷ Harvester capacity (EFC) (ha/hr.) (SDG /ha)

2.9.5 Number of required machines in field operations:

Required Number of machines = Area to be covered (ha) ÷ effective machine capacity EFC (ha/hr) × total working hours per season (hr)

Number of required machines $= \frac{A}{EFC \times Ann\ hrs}$

Where,
A = area to be covered (ha)
EFC = effective field capacity (ha/ hr),
Ann. hrs.. = annual hours of use.

2.10 computer system validation and verification

Computer system validation and verification are carried out to test the system accuracy to estimate various machine capacities, fuel consumption, and different machine costs correctly and compare the results with actual calculation (scientific calculator).

2.11 Sensitivity statistical analysis and computer system accuracy tests

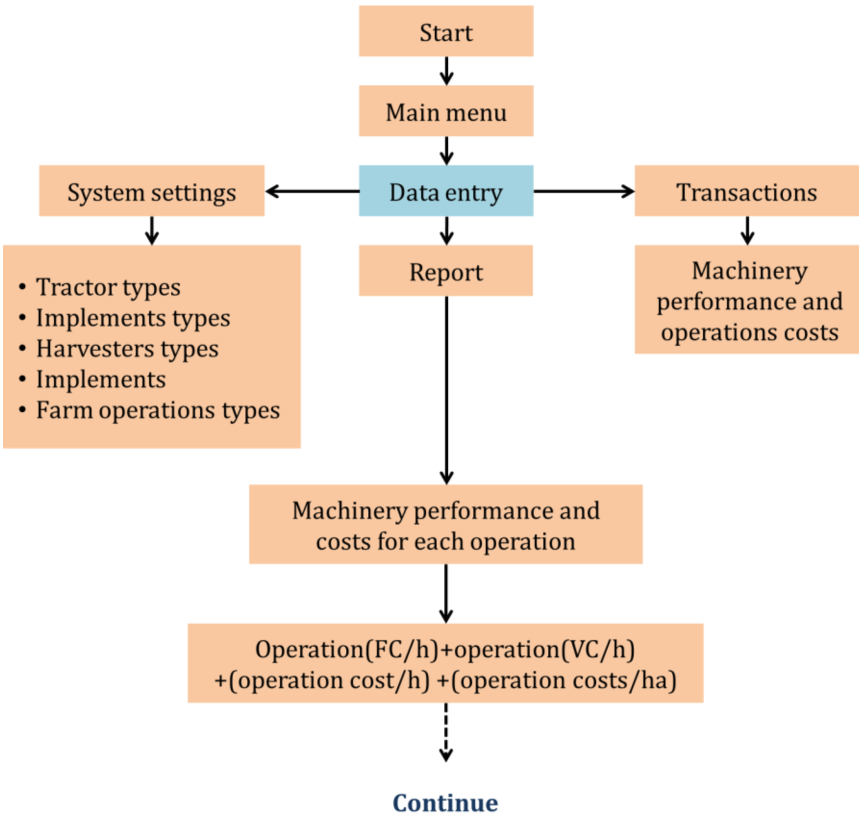
The sensitivity analysis of the system was carried out to show the effect of changing one or more of the input data in each unit on the system outputs. It was also carried out for the field operation cost unit to detect the response of the developed system to the changes in some input data on the system output. T-test statistical techniques will be applied to test the developed system's accuracy compared with the actually applied procedure in the study area.

2.12 Field operations machinery system maximization problem

For the three operations (Land preparation, planting, and harvesting), budgets were assumed for the total area of 50000 ha (120000 feddan). Total calendar days, working hours per day, and total working hours in the field for the whole season were found. The productivity (EFC) of the machinery system per day and per hour was calculated for the machines used. Effective field capacities (EFC) for each utilized individual machine as a result of the system estimation (ha/hr) and (ha/hr) and operation cost (SDG/hr) used to formulate the problem. Accordingly, the objective function was used for optimization.

2.13 Sensitivity analysis of linear programming (LP)

It will be used to detect how the basic solution is sensitive to the changes in the input data (James and Leaven 1998). This sensitivity is done by changing the values of the right-hand side (RH) solution column (constraints) and changing the values of the objective functions' coefficients. Through this process, we can detect the effect of changing these values on the feasible basic solutions in each field operation.



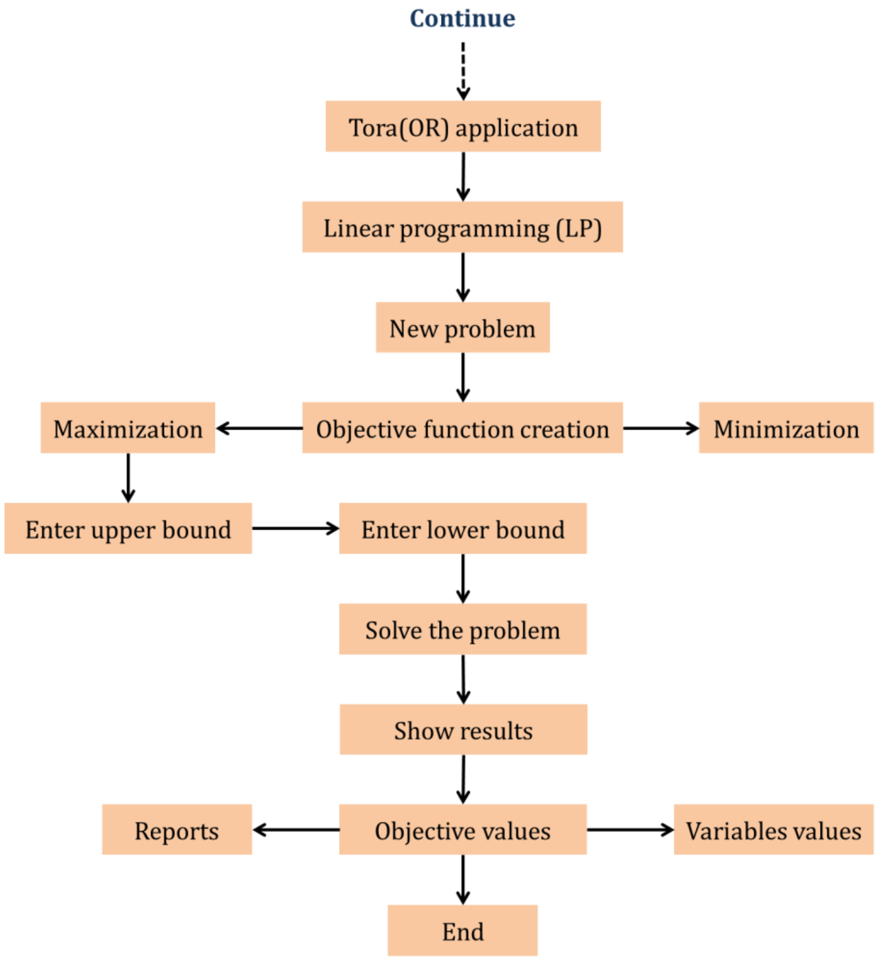


FIGURE 1: Program flowchart.

3. RESULTS AND DISCUSSION

3.1 Computer system development

A computer system was developed in the C^{++} programming language to predict the field performance of tillage operations, planting, and harvesting operations, in addition to the fixed and variable costs. The developed computer system was significantly used for the prediction of machinery field performance and costs, which were formulated for objective functions and optimization that contributes to the increase in crop productivity of wheat under the Northern State of Dongola area.

3.2 Predicted and actual effective field capacity (EFC) in ha/h for land preparation, planting, and harvesting machinery operations

The developed computer system was validated by comparing the predicted results with actual field data (Table 2). Some published data collected from different relevant literature (ASAE 2003 and Dahab 2000) were used to verify the developed system. Three land preparation operation machines namely (chisel plow 7 shanks (1.9m), Offset disc harrow 24(2.7m) and offset disc harrow 32 (3.65m)), three planting (ATTESPAR drill (3.00m), Agro-master drill (3.30m) and Baldan drill(4.00m)) and three types of combine harvesters FOTTON 4Lz2 (2.70m), SONALIKA International (4.20m) and Class dominator 130 (4.30m)) were used to predict the effective field capacity (ha/h) and compared with the actual effective field capacity.

The results showed that for the land preparation implements, the actual effective field capacities were significantly higher as compared to the predicted ones. The results were in conformity with the results obtained by Siemens *et al.* (1999) and Yousif (2011), who mentioned that field capacity is significantly affected by machine working speed and field efficiency. Moreover, there was a strong positive correlation between the predicted and actual EFC (R^2 = 0.968). This confirms that the developed program is valid to estimate EFC for machinery with a high level of accuracy.

Planting operation results revealed that the system prediction of effective field capacity was higher as compared to the actual field values for three types of planting machinery, ATTESPAR drill (3.00m), Agro-master drill (3.30m), and BALDAN drill (4.00m). They increased the EFC by 20%, 17% and 28%, respectively. The width of the machine was found to have a noticeable effect on improving the field efficiency, as reported by Hunt (2008).

The statistical analysis of paired samples correlations (predicted and actual EFC) for planting machinery showed strong positive correlations between the two pairs (R^2 = 0.974). This proves that the developing program is valid to estimate EFC for planting machinery with a high level of accuracy. For the harvesting machinery, the results showed that the predicted EFC was significantly higher than the actual by 13%, and 19% for SONALIKA international combine harvester (2.20m) and 19% for FOTTON 4Lz2 (2.70m) respectively, while it decreased by 4% for Class dominator 130 combine harvester (4.30m). On the other hand, the results showed very strong positive correlations between the two paired (R^2 = 0.950). The results confirmed that the developing program is valid to estimate EFC for all used machines with a high level of accuracy. The results agreed with the results obtained by Siemens *et al.* (1999).

TABLE 2: Comparison between system-predicted and actual effective field capacity EFC (ha/h) for land preparation, planting, and combine harvesting machines.

Operation	Machine	Predicted EFC	Actual EFC	Comparative (%)
Land preparation	Chisel plow 7shanks (1.9m)	1.39	1.58	88
	Offset disc harrow 24 (2.7m)	1.97	2.1	94
	Offset disc harrow 32 (3.65m)	2.67	2.81	95
Planting	ATTESPAR drill(3.00m)	2.02	1.68	120
	Agromaster drill (3.30m)	2.2176	1.89	117
	Baldan drill (4.00m)	2.688	2.1	128
Harvesting	FOTTON4Lz2 (2.70m)	0.945	0.788	119
	SONALIKA International (4.20m)	1.4945	1.313	113
	Class dominator 130 (4.30m)	1.505	1.575	96

3.3 Estimation of machinery costs for land preparation, planting, and harvesting operations.

Table 3. showed that for the three operations, the system predicted lower total operation costs compared to the actual total operation costs when using chisel plow 7 shanks (1.90m), offset disc harrow24 (2.70m) and offset disc harrow 32 (3.65m) implements for land preparation, ATTESPAR drill (3.00m), Agro-master drill (3.30m) and Baldan drill (4.00m) for planting and SONALIKA international (2.20m), FOTTON 4Lz2 (2.70m) and Class dominator130 (4.30m) combine harvesters. The variations between the actual and predicted machinery costs may be attributed to the high market prices of spare parts and high percentage rates of inflation. The cost is also different from one machine to another may be due to variation in management policies and operator skills, as mentioned by Dahab (2013). Moreover, in developing countries, the cost of repairs is considerably higher due to high prices of spare parts and sometimes a lack of knowledge of proper operation and maintenance, as stated by Hunt (2008). Statistical analysis of paired samples correlations (predicted and actual total operation costs) for all machinery used showed strong positive correlations (R^2 = 0.885). The results confirmed that the developed program is valid to estimate total operation costs for the three operations with a high level of accuracy.

3.4 Sensitivity analysis of the system to estimate machinery effective field capacity (ha/h)

The sensitivity analysis of the system was carried out to show the effect of changing one or more of the input parameters on the program outputs. The input variables include machine width or size (m), speed (km/h), and expected field efficiency (%). The three planting machines, ATTESPAR drill (3.00m), Agro master drill (3.00 m) and Baldan drill (4.00m) and the three combine harvesters, Class dominator 130 (4.30m), SONALIKA international (4.27 m) were used to test the effect of changing machine width on their capacities (EFC).

TABLE 3: Comparison between systems' predicted total costs and actual total costs.

Operation	Machine	Predicted total operation costs (SDG)	Actual total operation costs (SDG)	Comparative (%)
Land preparation	Chisel plow 7shanks (1.9m)	93419.2225	125520	74
	Offset disc harrow 24 (2.70m)	155038.882	177184	88
	Offset disc harrow 32(3.65m)	182657.6505	273794	67
Planting	ATTESPAR drill(3.00m)	177166.7624	205400	86
	Agromaster drill(3.30m)	171353.5248	195700	88
	Baldan drill(4.00m)	187210.6567	225600	83
Harvesting	FOTTON 4Lz2 (2.0m)	174841.33	202400	86
	SONALIKA International (4.27m)	150743.116	186644	81
	Class dominator 130 (4.30m)	253587.82	279600	91

TABLE 4: Effect of increasing machine width on effective field capacity (ha/h).

Operation	Implement	Width (m)	Speed (Km/h)	Efficiency (%)	EFC (ha/h)
Planting	ATTESPAR drill	3.00 3.25	9.6	70	2.02 2.18
	Agro-master drill	3.30 3.45	9.6	70	2.22 2.32
	Baldan drill	4.00 3.30	9.6	70	2.67 2.89
Harvesting	Class dominator 130	4.30 5.00	5.00	70	1.51 1.75
	SONALIKA International	4.27 4.45	5.00	70	1.49 1.56
	FOTTON4Lz2	2.27 5.30	5.00	70	0.95 1.86

It was observed that as the width increased, the effective field capacity (EFC) generally increased by different values (Table 4). Therefore, increasing the working width of the machine significantly increased the effective field capacity as mentioned by Siemens *et al.* (1999) and Hunt (2015).

Table 5 showed that the effective field capacity was significantly increased by increasing working speeds, but with different percentages for the different planting and combine harvesting machines. The obtained results showed that any increase in the implement working speed increased effective field capacity (ha/h), but this increase should be limited to an extent that keeps the implement operating to its optimum quality. The results were in agreement with those obtained by Siemens *et al.* (1999) and Elbashir (2015). As presented in Table 6, the effective field capacity of all machinery used was significantly affected by changes in field efficiency. The obtained results showed that any decrease in the field efficiency resulted in a decrease in machine effective field capacity (ha/h). The results were in agreement with those obtained by Elbashir (2015).

TABLE 5: Effect of increasing working speed on machine EFC (ha/h).

Operation	Machine	Width (m)	Speed (km/h)	Efficiency (%)	EFC (ha/h)
Planting	ATTESPAR DRILL	1.9	9.6 11	70	2.02 2.31
	Agromaster drill	3.30	9.6 11	70	2.22 2.54
	Baldan drill	4.00	9.6 11	70	2.69 3.08
Harvesting	Class dominator 130	4.30	5.00 7.00	70	1.51 2.11
	SONALIKA International	4.27	5.00 7.00	70	1.49 2.09
	FOTTON4Lz2	2.70	5.00 7.00	70	0.95 1.32

TABLE 6: Effect of decreasing machine efficiency on EFC (ha/h).

Operation	Machine	Width (m)	Speed (km/h)	Effic.(%)	EFC (ha/h)
Planting	ATTESPAR drill	1.9	9.6	70 65	2.016 1.8721
	Agro-master drill	3.00	9.6	70 65	2.2176 2.0592
	Baldan drill	4.00	9.6	70 65	2.688 2.496

Operation	Machine	Width (m)	Speed (km/h)	Effic.(%)	EFC (ha/h)
Harvesting	Class dominator 130	4.30	5.00	70	1.505
				60	1.29
	SONALIKA International	4.27	5.00	70	1.4945
				60	1.281
	FOTTON4Lz2	2.70	5.00	70	0.945
				60	0.81

3.5 Effect of the developed system on decision making

As shown in Table 7, the developed system had the ability to predict No. Of required machine as well as the number of required laborers, in addition to the total cost, and machine performance for each operation. For land preparation, it requires 66 small-sized machine chisel plows 7 shanks (1.9m) with an EFC (1.39 ha/h) and 132 laborers with 169.85 SDG per hour. For the planting operation, it requires 48 small machine size ATTESPAR drill (3.00m) (2.02 ha/h) and 96 laborers and operation costs per hour of 340.71 SDG/h. while for the harvesting operation, it was required 69 small-sized combine harvesters (2.70 m) (0.95 ha/h) and 138 laborers, and the operation cost per hour of 228.55 SDG.

Relying on small machines will increase the risk of inability to operate (land preparation, planting, or harvesting) in time due to their small capacity (EFC), while medium machine sizes need a smaller number of machines and laborers than small ones, but higher costs should be considered. On the other hand, large machines require a smaller number of machines and labor to operate. The risk of timeliness is reduced during the peak period to its minimum due to the large machine capacity (EFC). Hence, optimization of different machine capacities (EFC) becomes the best choice to be adopted to utilize time, operation costs (SDG/h), and other production resources as mentioned by Dahab (2013). Moreover, the system output enables Agricultural System Managers (ASM) to better manipulate and save production resources.

According to Table 7, the options and Objective functions of the three operations are as follows:

(a) Land preparation:

Max (Z) = $1.3877X_1 + 1.9720X_2 + 2.6659X_3$ Subjected to: $169.85313X_1 + 295.93433X_2 + 332.10481X_3 + \leq 152727.2727$ budget constraints (assumed budget /annual hour of use (SDG/h)

$X_1 + X_2 + X3 \leq 133$ (total numbers of available implements (constraint) $10X_1 + 10X_2 + 10X3 + \leq 550$-time constraint (annual hours of use).

(b) Planting operation machine:

Max (Z) = $2.016X_1 + 2.2176X_2 + 2.688X_3$ Subjected to: $340.7053X_1 + 329.5260X_2 + 360.02049X_3 \leq 23076.92308$ budget constraints (assumed budget / annual hours of use, SDG/hr.).

$X_1 + X_2 + X3 \leq 88$ (total numbers of available implements (constraint)

$13X_1 + 13X_2 + 13X_3 \leq 520$-time constraint (annual hours of use).

(c) Harvesting operation machine:

Max (Z) = $0.945X_1 + 1.4945X_2 + 1.505X_3$ Subjected to: $228.55075X_1 + 1970.4982X_2 + 331.48734X_3 \leq 94117.6470$ (budget constraints)

$X_1 + X_2 + X3 \leq 55$ (total number of available machines)

$17X_1 + 17X_2 + 17X_3 \leq 765$ (time constraint (annual hours of use).

3.6 Optimization of size and cost for land preparation, planting, and harvesting operations

As presented in Tables 4.8a, 4.8b, and 4.8c, the number after optimization significantly decreased, and consequently, the overall operation cost per hour for land preparation, planting, and harvesting operations decreased. Small size implements (1.90m) reduced cost operation from 11210.31 SDG to zero cost (reduction percentage 100%), while for medium size implements (2.70m) reduction percentage was 54%. On the other hand, the overall operation costs per hour for large-sized implements (3.65m) and large harvesting machines (4.30m) do not change because the required number of machines does not change after optimization. A similar trend was observed for the other two operations. Hence, the model output enables Agricultural System Managers (ASM) to manage production resources with the most cost-effective or higher achieved performance under the given constraints by maximizing desired factors and minimizing undesired ones.

TABLE 7: Machinery options for land preparation, planting, and harvesting operations.

Operation	Machine	Size (m)	EFC (ha/h)	No. of required machines	No. of required laborers	Cos per hour(SDG)
Land preparation	Chisel plow7shanks	1.90	1.39	66	132	169.85313
	Offset disc harrow24	2.70	1.97	46	92	295.93433
	Offset disc harrow32	3.65	2.67	34	68	332.10481
Planting	ATTESPAR drill	3.00	2.02	48	96	340.7053
	Agromaster drill	3.30	2.22	43	86	329.5260
	Baldan drill	4.00	2.69	36	72	360.02049

Operation	Machine	Size (m)	EFC (ha/h)	No. of required machines	No. of required laborers	Cos per hour(SDG)
Harvesting	Fotton4LZ2	2.70	0.95	69	138	228.5507
	SONALIKA International	4.27	1.49	44	88	1970.4982
	Class dominator 130	4.30	1.51	43	86	331.4873

TABLE 8a: Effect of optimization on the implementation operation cost per hour for land preparation operation.

Implement name &size	Required No. before optimization	Required No, after optimization	operation cost (SDG/h)	Overall implementation cost (SDG/h) before optimization	Overall implements cost (SDG/h) after optimization
Chisel plow 7 shanks(1.9 m)	66	0	169.85313	11210.30658	0
Offset disc harrow 24 (2.70 m)	46	21	295.93433	13612.97918	6214.62093
Offset disc harrow 32 (3.65 m)	34	34	332.10481	11291.56354	11291.56354
Total operation costs (SDG/h)				36114.8493	17506.18447

TABLE 8b: Effect of optimization on implementation operation costs (SDG/h) for planting operation.

Implement name &size	Req. No. before optimization	Req. No. after optimization	Operation cost (SDG/h)	Overall implementation costs (SDG/h) before optimization	Overall implementation cost (SDG/h) after optimization
ATTEPAR drill (3.00)	48	0	340.7053	16353.8544	0
Agro master drill (3.30)	43	4	329.5260	14169.618	1318.104
Baldan drill (4.00m)	36	36	360.0204	12960.7344	12960.7344
Total operation costs (SDG/h)				43484.2068	14278.8384

TABLE 8c: Effect of optimization on combine harvester's operation costs per hour.

Combine harvester name & size	Required No. before optimization	Required No. after optimization	Operation costs (SDG/h) before optimization	Overall harvesters' cost (SDG/h) before optimization	Overall harvesters' costs SDG/h after optimization
FOTON 4Lz (2.70m)	69	0	228.5506	15769.914	0
SOALIKA International (4.27m)	44	2	1970.4982	86701.9208	3940.9964
Class dominator 130 (4.30)	43	43	331.4873	14253.9539	14253.9539
Total operation costs (SDG/h)				116725.7887	18194.9503

3.7 Sensitivity analysis of linear program (LP) solution for land preparation, planting, and harvesting operations

Sensitivity analysis was carried out to investigate how the (LP) solution is effective to change in data. When using the simplex algorithm automatically, we get sensitivity information as a byproduct of using the simplex algorithm. The output of the simplex method gives information about what happens when we change the right-hand side (RHS) of a constraint equation on the objective function (max) value and on decision variables.

Table 4.9a shows the sensitivity analysis of (LP) for land preparation operation and illustrates that the change by a decrease in the right-hand hand side (RHS) budget constraint (SDG) translated into changes in the feasible region of the solution, and it gives us a new optimal solution with a new objective value lower than the first optimal solution (109.02 ha/h). On the other hand, decreasing the (RHS) number of available implements constraint, a new optimal solution with a new objective value is obtained (122.20 ha/h), which is lower than the first optimal solution and more than the second optimal solution. While increasing the (RHS) annual hours of use constraint, translated into changes in feasible solution, a new optimal solution is obtained with a new objective value (161.64 ha/h), which is the highest optimal solution among the others. Sensitivity analysis of (LP) for planting operation revealed that, decreasing (RHS) budget constraint (SDG) leads to changes in the feasible region of the solution, and it gives a new solution with a new objective value (89.60ha/h) which is lower than the first optimal solution as shown in Table 4.9b. While increasing the (RHS) annual hours of use constraint, translated into changes in feasible solution, and therefore a new optimal solution is obtained with a new objective value (164.86ha/h), which is the highest among the others. On the other hand, Table 4.9c for the sensitivity analysis of (LP) of harvesting operation showed that decreasing (RHS) budget constraint (SDG) is translated into changes in the feasible region of the solution, and it gives a new optimal solution with a new objective value (67.33ha/h) lower than the first optimal solution, while increasing the (RHS) annual hours of use constraint, translated into changes in feasible solution resulted with a new objective value (82.66ha/h). The results were in agreement with Taha (2011) and the results obtained by Belel *et al.* (2014), who mentioned that the selection of the optimum width of implements was found to have a noticeable effect in improving the field capacity and efficiency.

TABLE 9a: Sensitivity analysis of linear program (LP) solution for land preparation operation.

Type of the changed constraint	Constraints value	Decision variables	Solution value	Objective function (max) value
Budget/h (SDG)	152727.27	x_1	0	
Available number of implements	133	x_2	21	132.02
Annual hours of use (h)	550	x_3	34	
	13500	x_1	**29.39**	
Decreasing RHS (Budget/h)	133	x_2	0	**109.08**
	550	x_3	25.61	
	152272.27	X1	0	
Decreasing RHS (total number of implements)	50	X2	**16**	122.20
	550	X_3	34	
	152272.27	X_1	0	
Increasing RHS (annual hours of use)	133	X_2	36	161.64
	700	X_3	**34**	

TABLE 9b: Sensitivity analysis of linear program (LP) solution for planting operation.

Type of the changed constraint	Constraints value	Decision variables	Solution value	Objective function (max) value
Budget/h (SDG)	23076.92	x_1	0	
Available number of implements	88	x_2	4	105.64
Annual hours of use (h)	520	x_3	36	
	12000	x_1	**0**	
Decreasing RHS (Budget/h)	88	x_2	0	**89.60**
	520	x_3	33.33	
	23076.92	x_1	0	
Decreasing RHS (total number of implements	30	x_2	**0**	80.64
	520	x_3	30	
	23076.92	x_1	0	
Increasing RHS (annual hours of use)	88	x_2	30.7	164,86
	900	x_3	**36**	

TABLE 9c: Sensitivity analysis of linear program (LP) solution for harvesting operation.

Type of the changed constraint	Constraints value (RHS)	Decision variables	Solution value	Objective function (max) value
Budget/h (SDG)	94117.6470	X1	0	
Available number of harvesters	55	X2	2	67.71
Annual hours of use (h)	765	X3	43	
Decreasing RHS (Budget/r)	17000	X1	**0**	
	55	X2	1.31	**67.33**
	765	X3	43	
Decreasing RHS (total number of harvesters)	94117.6470	X1	0	
	40	X2	**0**	60.20
	765	X3	4	
Increasing RHS (annual hours of use)	55	X1	0	
	94117.6470	X2	12	82.66
	1000	X3	**43**	

CONCLUSIONS

The following conclusions may be drawn from the present study:

(1) The developed system is user-friendly and could be run on most available computers and composed of two sections, section one contains, machinery performance and costs estimation units, Section two used to solve the generated linear program (LP) production problem through applying linear program (LP) software (Tora) and using simplex method to obtain the optimization of sizes and costs of machinery used for wheat production in Dongola area.

(2) The developed system was statistically validated and analyzed by comparing the predicted results to the actual data, and proved to be fairly accurate.

(3) Linear and integer programming (LP) software (Tora) was used in the maximization problems to optimize machinery sizes and costs for machinery used for wheat production and the required numbers after optimization were zero for small sized machinery and 21,4 and 2 for medium size machines of land preparation, planting and harvesting operations respectively, while for the large machines the numbers were 34, 36 and 43 machines in sequence.

(4) Optimization of machine capacities enables managers to better control machine fleet size during critical time periods to successfully complete the selected operations, and to forecast the expected need for additional power units to meet the expansion requirement of production.

(5) The system concept was a suitable approach adopted to manage and organize machinery as a group of components, operational functions, and processes that are integrated to accomplish a well-defined purpose (optimization).

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