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Predicting the optimal replacement time for farm power and machinery using a computer programme

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ABSTRACT

The least-cost machinery selection and replacement was determined in this paper, taking into account fixed, variable and timeliness costs. Replacement models for the medium size diesel-engine tractors (MF 265) were developed and solved using a microcomputer programme written in Dbase. Data obtained from agricultural mechanization schemes in two agricultural zones of Anambra State, Nigeria was used in testing the models. Tractor cumulative use was shown as the major determinant of tractor repair and maintenance costs, and therefore a major factor in the replacement decision. The remaining value of the tractor decayed exponentially with age showing the case is suitable for deterministic replacement modelling. The equivalent average annual operating cost of the tractor under the studied techno-economic situation decreased steadily with tractor age, hit a minimum value of ₦137,835.98 at year Five, and thereafter increased. The optimum replacement period was therefore shown to be Five years. The equivalent cost followed a 2nd order polynomial trend. The R^2 value of 0.9952 and 0.9315 for the tractor's book value and the equivalent annual operating cost respectively indicated good prediction with the models. Poor book keeping was challenging to successful computerization of agricultural machinery management. It affects timely replacement of machinery and ultimately the cropping operations timeliness, crop yield and profitability of the farm enterprises.

1. Introduction

Mechanization is essential in agriculture. It ensures timely completion of farm operations, reduced drudgery and lower cost per unit area, making farming attractive [1,2]. With the farm labour loss to urban occupations [3], the tractor has become the major power unit in farm operations. The versatile applications of the agricultural tractor, its high power output and mobility make the tractor a cost-effective replacement for farm labour. This makes tractor availability a high ranking farm production factor.

Appropriate Machinery Selection: For minimum-cost machine selection timeliness cost penalty is levied on the proposed machines. The penalty is valued as the possible farm product's quantitative or qualitative losses from a machinery's inability to complete the farm operation timely [4]. Equally, machinery availability and timely replacement is needed to enhance the profitable utilization of the machinery over its life cycle. The right criteria is therefore needed for selecting the appropriate power units for timely completion of agricultural operations at a minimum cost and reduced drudgery. For satisfactory machinery performance and economics, [5] opined that the tractor and its associated machines must be adaptable to the crops and farm size.

Farm machinery ownership costs are fixed costs like depreciation, insurance, shelter, taxes and interest charge which are seemingly independent of use. Operation or variable costs, on the other hand vary with machinery use. They include costs of maintenance, repairs, labour, oil, lubricants and fuel. [6] suggested straight-line method as most convenient for approximating machinery costs. However, alternative methods that quickly recover the cost of the equipment at the early stage of the life are preferable where inflationary trend makes price forecast uncertain.

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Farm size, soil conditions, cropping pattern, cultural practices, yield, and purchase price of machines influence the farm power and equipment selection for given farm operations. Enhanced annual machine use, and reduced operational costs and energy consumption influence the net return on investment for a given farming situation. Annual machine use is affected by the selected power-implement system. The massive devaluation of the Naira has led to prohibitive rise in the costs of farm machinery and spares procurement, their repair and maintenance, and replacement. The multiple variables involved and their complex interactions make the already onerous machinery selection and replacement decisions even more daunting. The variables include modifying the list price to account for inflation. Except for the very simple systems, selection of the appropriate minimum-cost tractor and associated implements are accomplished using digital computer programmes [7]. The data security and fast retrieval required for the machinery selection, maintenance, replacement and other management decisions are made easy with such programmes.

Machinery Selection Models: Mathematical models mostly used in farm machinery management are tailored to a particular region or situations. They include least-cost mathematical models, linear programming models, activity or event network analysis models and heuristics. Software developed in BASIC language can determine the optimum power requirement for a known farm size and operations using Hunt's least-cost equation for economic agricultural production [8,9,10]. These studies were able to predict, the number of tractors needed, implements required, annual cost of operating the equipment per hectare and per hour, operating hours for each equipment, fuel and oil requirement. [3] developed an optimal farm machinery selection program in BASIC language for vegetable planting. The output included tractor and machinery size and cost, time of operation and returns. [4,11] developed tillage machinery selection models for single farm and for non-contiguous scattered farms cases. The models were evaluated with Microsoft Excel programmes. [12] used a deterministic DP model to audit the replacement policy of a locally-fabricated oil palm digester transmission unit.

Based on the available field work days (G) and daily working hours (B) a simple field machine capacity C_i required for processing a farm size A can be estimated as in Equation 1, as reported by [13].

$$C_i = \frac{A}{(B)(G)(\lambda)} \quad (1)$$

Definition of all variables used in this paper is listed at the end of the article.

Annual timeliness cost (Ω) is estimated for an operation from a timeliness coefficient (K) obtained from [13] as

$$\Omega = \frac{KA^2(Y)(yV)}{(Z)(G)(C_l)(\lambda)} \quad (2)$$

Optimum power required (P_{opt}) for the various field and transport operations (l and j) is calculated as follows [6]:

$$P_{opt} = \left[\sum(P_{dl}) + \sum(P_{Tj})\right]^{\frac{1}{2}} \quad (3)$$

Where: the required drawbar power (P_d) evaluation is based on hourly labour (L) and timeliness costs

$$P_d = \frac{100(A)(E)(n)}{r(FC\%)(P_{Pt})} \cdot \left[L + \frac{(K)(Y)(yV)(A)}{(Z)(N_t)(\lambda)(h)}\right] \quad (4),$$

the energy required by implement per hectare (E) for drawbar operation is given in kWh/ha as

$$E = \frac{10(BHP)(LCF)}{(w)(S)(e)} \quad (5)$$

and the power required for transport operations (P_T) is calculated as:

$$P_T = \frac{100(0.27)(D)(W)(L_T)}{(FC\%)(P_{Tt})} \quad (6).$$

The annual cost of an implement (AC) can be expressed as

$$AC = \frac{(FC\%)P}{100} + \frac{(c)(A)}{(S)(w)(e)}\left[(R\&M) + M + L + O + F + T\right] \quad (7)$$

Self-propelled machines have zero tractor cost per hour (T). Economic selection implies determination of the power or machine capacity with the lowest total cost. Such power or machine size balances the ownership costs against the opposed operation and timeliness costs. To evaluate it, the variables in Equation 7 are expressed in their per-effective machine width (w) form where possible. The AC equation is thereafter differentiated with respect to w. The minimum-cost w is solved from the derivative [6].

Machinery Replacement: Production machine may need replacement because of obsolescence and uneconomic repairs [14]. Inadequate capacity due to increased production scale or unacceptable availability from excessive downtimes also put a machine in need of replacement. When equipment deteriorates with usage and age, the performance at a point will fall below the set standard. In practice maintenance and replacement always overlap as most repairs and maintenance works consist of components or sub-assemblies replacement. The size of the machine, its list price and the amount of use influence maintenance cost [13]. [15] argued that repair and maintenance costs exhibit both fixed and variable characteristics. Holistic consideration of the prevailing circumstances is therefore needed for sound equipment maintenance and replacement decisions.

The deterministic replacement model evaluates the optimal replacement interval that minimizes the total operating cost per unit time. It is applied where the cost of operating the equipment increases with time [12]. The time value of money and accruing interest must be considered since the use period is sometimes indefinite. This requires maximizing the total discounted net benefits or minimizing its total discounted cost. The stochastic replacement case is applied to items that fail suddenly with a cost of failure and in some cases, safety risks to personnel. Failure time may be obtained by inspection or from the probability distribution of the age at which equipment fails. The aim of this study is to develop optimization models for farm machinery selection and replacement under given operating conditions. The results from the study case were compared with the policy in place. The replacement situation studied is for equipment with normal economic life (n).

2. Materials and Methods

2.1 Case Study

The data used for this work were gathered from Agricultural Engineering Department of Anambra State Ministry of Agricultural (MOA) and Agricultural Development Program (ADP) Awka. The farms from which field data were obtained include, Timex Farms Nawfija, World Bank Rice Project Enugu-Abor, and Ogboji Rice Project, all in Anambra State. These farms used tractors and equipment for the period of this data collection. Personal interactions were made with the managers and machine operators in the study area. The replacement costs items were computed at the prevailing rates and used to predict the optimal equipment replacement periods for the 8-year planning horizon for the deterministic case. The reliability of different replacement alternatives was compared.

The farm complex started operation in 1987 with two MF 265 tractors costing ₦48, 000.00 each, and their matching implements. The estimated service life was 10 years, the salvage value 10% of initial cost, while annual oil and diesel consumptions were 480 litres and 24000 litres respectively. At the end of its first year in service each tractor had 12 full services, 3 brake realignments and incurred 10% of the tractor price as combined cost of insurance, shelter, road fee, road worthiness and operators` license. Driver's salary was paid and a set of tyres changed. These were considered normal operating disbursements since they reoccur every year.

In determining the required optimum power (P_{opt}), the different crops' yield and operations' timeliness loss factors (K) were used. See Table 1. Local potential yield (Y) and current prices (yV) were considered but the values of (K) were based on those given by [16].

Table 1- Data of crop price, yield and timeliness loss factor

Parameter	Paddy	Maize	Wheat
*Yield (Y), Tonnes/ha	3.5	3.5	4.0
Timeliness loss factor (K):			
- Tillage & sowing	0.0065	0.0046	0.00465
- Harvesting & Threshing	0.0066	NA	0.00650

Source: [1]

*Paddy and maize yield data from studied farms

2.2 Machinery Costs Evaluation

2.2.1 Equipment ownership cost

Simple annual depreciation based on the straight line method and machine salvage value (S) deduction [6] was employed. Current market values were obtained while simple interest rate (i) of the average investment over the life of the machine (2nd term in Equation 8) was used. Taxes, shelter and insurance costs were combined and estimated as percentage (Q) of the purchase price. Total annual ownership costs was estimated by multiplying the purchase price of the machine by the decimal form of the ownership cost percentage (C_O) shown in Equation 9.

$$C_O = 100\left[\frac{1-s_V}{Li} + \frac{1+s_V}{2}I + Q\right] \tag{8}$$

2.2.2 Equipment operating costs

Repair and maintenance costs were expressed in an accumulated mode to reduce variability. Labour cost is obtained from the salary and wages of the operators involved in the tractor operation. Oil and lubricant expenses are collated and integrated into the variable cost. Zero tractor cost was used since it is the object of the selection.

2.3 Replacement Decision

The deterministic method was used, and consisted of determining the present worth (PW_{t-m}) of the various possible equipment replacement routes. Solving the dynamic programming (DP) recursive equations (Eq. 10) gave the least cost route; which specifies the optimum replacement policy.

$$\underset{U_m}{min} = t(K_t + PW_{t-m}) \tag{10}$$

2.4 Computer Program Development

2.4.1 The programme and system design

The system provided decision support models for detailed and interactive machinery selection, maintenance and deterministic engineering replacement decisions for equipment with normal economic life (n). This program is capable of computing the present worth of equipment and the time in which total operating cost is minimal within the service life under deterministic conditions.

i. It allows immediate access to the system when a disbursement record needs to be updated, displayed, or printed and also in calculation of minimum present values.

ii. It has input and output control in case of displaying or printing, and editing existing records.
iii. It allows updating and retrieval of information of any replacement parts at any point in time.
iv. Provision of storage media so that records will be stored temporarily and permanently.

It generates and displays the values of operating disbursements, book values, present worth of costs, discount factors, and calculates the minimum present cost for the planning horizon.

The program was structured; in modules of sub-programs that are coordinated by the main program. See the appendices. The programming language used is DBMS-DBase III +, because of its simplicity in handling large data such as the disbursement records of the case study.

2.4.2 Operational guide and installation requirements

The minimum installation requirements for the programme are: 386 MHz and above processor, Internal memory RAM of about 576 kB, 80 MB Hard disc, Compound disc or flash drive, Parallel printer, Line printer, Colour monitor, UPS 60 V. Ability to use the computer and availability of Dbase III + in MS-DOS operating environment is required. Steps involved in using the program are as follows:

1. Switch on the system and allow it to boot.
2. Restart the computer in DOS environment.
3. At command prompt type DBASE and press Enter key to load the program
4. Then press Escape key to get to the menus of the application program.
5. At the dot-prompt type DO TRACTOR and press enter key.
6. Programmer/ user then interacts with the program menus displayed by system.

2.5 Execution and Validation of the Model

Deterministic model was chosen for the tractor's replacement analysis since agricultural tractors deteriorate with age and use. This should be evidenced in the book value (BKV_t) and present worth (PW_{t-m}) for successive years [17] using Eqs. 11 and 12.

$$BKV_t = P - \{t(2N + 1 - t)(P - Sv)\}/N(N + 1) \quad (11)$$

The present worth (PW_{t-m}) was obtained from disbursements (D_k) as

$$PW_{t-m} = PW_t + \sum_{k=t+q}^{m} D_k\,(p/f, i, q) - Sv_m(p/f, i, q) \quad (12)$$

The (PW_{t-m} of all D_k over the equipment's life gave a fixed annual payment based on the discount factor $V = (1 - i)^{-k}$; as

$$PW_n = (P - V^k Sv_k + V^n R_n)(1 - V)/(1 - V^k) \quad (13)$$

The DP equation denoted by the average annual machine cost function chooses the k value which minimizes the equivalent cost

$$F(k) = min\left(P - V^k Sv_k + \sum_{k=0}^{k-1} V^k R_k\right)(1 - V^k)^{-1} \quad (14)$$

The calculated values of k and corresponding costs were examined for optimal value of k.

$$P - V^k Sv_k + \sum_{n=0}^{k-1} V^n R_n = PW_{t-m} \quad (15)$$

$$F(k) = PW_{t-m}/1 - V^k \quad (16)$$

Solving Equation 10 recursively gave the least cost k, and the data for "replace" or "continue use" decision of equipment; that is the optimum replacement policy for the planning horizon.

3. Results and Discussion

3.1 Interpretation of Results

The present worth PW_{t-m}, operating disbursements D_k and book value BKV_t of the tractors are shown for the years of operation t in Figure 1. The present worth exhibited logarithmic growth trend. See Equation 17. The growth rate slowed down as the age increased showing that the discounted value of the tractor decreased continuously, as the tractor aged. The 0.9934 R^2 value showed that the PW_{t-m} can be reliably predicted as logarithm function. The disbursement values D_k was fluctuating as the operation time increased; but with an increasing latter values. The trend (see Equation 18) shows that the maintenance expenses increased with increasing tractor life and use. The rate of increase was more pronounced at the latter stage of the tractor's life. The R^2 value showed that the 2nd order polynomial function predicted the variation well. The BKV_t had an exponential decay trend. See Equation 19. The remaining value of the tractor had a continual decay as the service year increased, indicating that the tractor deteriorated in value continually. The 0.9952 R^2 value showed that exponential predicted the remaining tractor value well. [12,17] have reported that deterministic replacement models are suitable for equipment that deteriorate with time.

$$PW_{t-m} = 42455ln(t) + 49649 \qquad R^2 = 0.9934 \quad (17)$$

$$D_k = 1234t^2 - 5882.1t + 51345 \qquad R^2 = 0.9273 \quad (18)$$

$$BKV_t = 48899e^{-0.248t} \qquad R^2 = 0.9952 \quad (19)$$

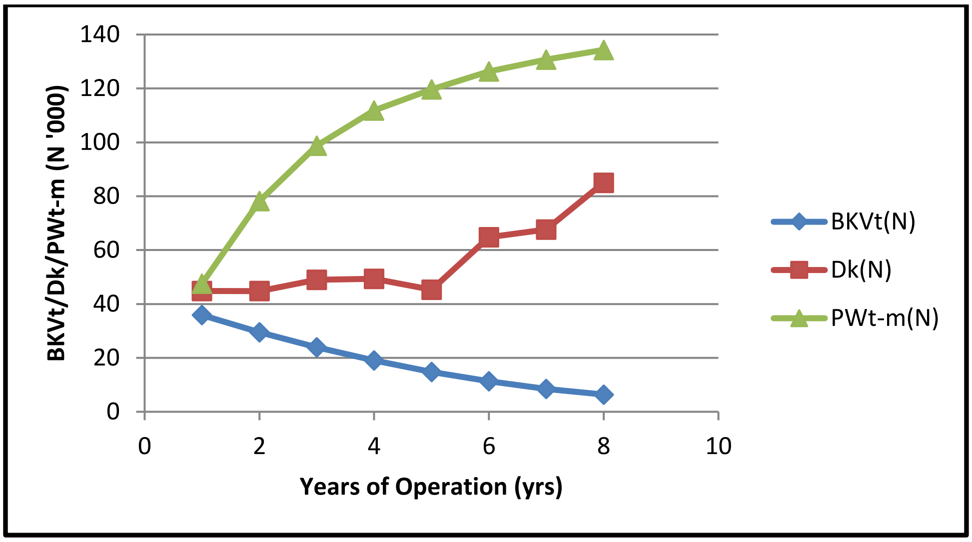

Fig.1 - The costs of machinery use for the years of operation

The present worth of the average annual replacement cost *F(k)* for the various planning periods are shown in Figure 2. The average cost varied as a 2nd order polynomial function with increasing tractor age. See Equation 20. The R^2 value of 0.9315 indicated that the average cost can be predicted well

$$F(k) = 206.52t^2 - 2305t + 144897 \qquad R^2 = 0.9315 \tag{20}$$

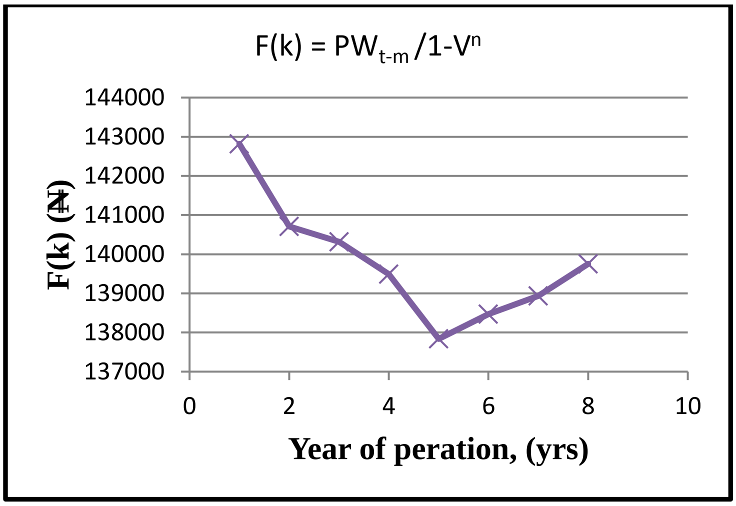

Fig. 2 - Present worth of the average annual replacement cost for 8 years operation

by the polynomial function. *F(k)* is minimum at *F(5)* = 137835.98 in Year 5 (k = 5). This shows that for the planning period, the cheapest alternative is to allow the tractor in service from the time of purchase to the end of the fifth year, while giving it only maintenance and overhauls. However, the practice in place from the interactions with operators of the tractors and machinery is to keep using them irrespective of the increasing operating costs until they are inoperable. The ever rising costs of replacement parts make it more difficult for the owners of the business to consider replacing the equipment within the plan period. [15] obtained the economic life for MF 285 tractors in Iran as 14 years. The tractors were depreciated using the declining balance method which results in reduced total cost during the equipment's later age. High repair and maintenance cost also correlates with reduced replacement period [6]. A least-cost replacement age of 4 years was obtained by [12] for a locally-fabricated oil palm digester transmission unit using the DP model. However, the local operators also followed the practice of using the units until they were unserviceable, without minding if a different replacement policy will afford a reduced operational cost.

3.2 Financial Implication

Computerization will add to the cost of computer system, while the required training for its operation and other accompanying facilities will increase the running cost of the company. The net benefit (ease of work and timeliness of operations) will however justify the procurements' initial capital outlay. Improvements are not without some costs to the beneficiaries. Manual method of handling equipment maintenance and replacement records was found inadequate. Computerization automates this bulky and time consuming exercise and makes it faster. Updating, editing, analysis and recall of equipment data are also easily made at any point in the machine's life. This model will also improve the efficiency of data processing in large establishments of similar industry. A manager can also predict the techno-economic condition of any machine at any time, which reduces time and efforts required for decision taking.

4. Conclusions

The optimum replacement period for the MF 265 tractors deployed some agricultural mechanization schemes in Anambra State, Nigeria was predicted using a deterministic replacement model, based on the equivalent average annual operation cost. While the present worth exhibited logarithmic growth trend for increasing operation time, the annual operation cost was fluctuating; but with an increasing latter values. The average discounted operation cost had a minimum value in year 5, showing the fifth year as the optimum replacement period. The cost followed a second order polynomial trend with a good predictability; R^2 value of 0.9315. The remaining value of the tractor had an exponential decay trend showing that the tractor deteriorated with age and use, and that the tractor techno-economic environment is suitable for the deterministic replacement modelling used. The predicted optimum replacement period of 5 years was much shorter than the 14 years economic life obtained by [15] for MF 285 tractors in Iran; possibly because of high inflation and other adverse techno-economic reasons. It is recommended that optimal replacement can be achieved by keeping good maintenance records, refurbishing, reconditioning and timely replacement of the machines.

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Symbols and Nomenclature

A = Area under cultivation with the crop/ implement, ha
AC = Annual cost of operation of implement, ₦/year
B = Number of days within the operation period, day
BHP = Brake power, kW
BKV_t = Book value of the equipment at time t, ₦
c = Constant, 10
C_i = Required machine capacity (based on available working days), ha/h.
C_O = Ownership cost percentage, %
D = Distance to be transported, km
D_k = Operating disbursement at stage k, ₦; can also be trade-in value (S_k) at stage k
E = Energy required by implement for drawbar operation, kWh/ha
e = Field efficiency of implement, decimal
F = Fuel cost, ₦/h
$F(k)$ = Average annual machine cost function
$FC\%$ = Fixed cost percentage of tractor or implement price, %
G = Expected available time for field work each day, h/day;
h = Actual number of hours utilized
I = Interest as compounded q times per year;
i = Interest rate, decimal (may be combined with inflation rate and rate of return may also be used)
j = Subscript referring to specific transportation operations
k = Intermediate stage variable; year at which replacement decision is analyzed
K = Timeliness loss factor, day^{-1}
K_t = Minimum cost of getting to state t, m years from which replacement is being considered
Li = Machine life, yrs
L = Operator’s wages for field operation, ₦/h
l = Subscript which refers to specific operations of implements
LCF = Load coefficient factor
L_T = Labour cost of transportation, ₦/h
N = life of the investment, yrs
n = Number of operation in a season
N_t = Number of times area should be divided because of dispersed optimum times
O = Oil cost, ₦/h
P = Initial machine cost/ list price, ₦ (In rapid inflation P is modified by interest and inflation rate)
p/f = Cost recovery factor for finding present value when the future value is given
P_d = Power required at drawbar for field operations, kW
P_{opt} = Optimum tractor power required, kW
P_{Pt} = Tractor price per unit rated power under field operation, ₦/kW
P_T = Power required for transport operations, kW
P_{Tt} = Tractor price per unit rated power under transportation, ₦/kW
PW_t = Present worth at time ‘t’, ₦
PW_{t-m} = Present worth of equipment at ‘t’ and terminates at m, ₦
q = Discount period

Q = Ownership cost factor for taxes, housing, and insurance; expressed as % of initial cost
R = 1 of a series of equal payments due at the end of each compounding period, q times per year;
r = Ratio of drawbar power to rated engine power
R&M = Repair and maintenance cost, ₦/h
R_n = Disbursements or (S_k), ₦
S = Speed of implement, km/h
Sv = salvage value, ₦
s_V = Salvage value factor of machine at end of machine life (year *Li*); decimal
t = Stages, 0, 1, 2, …t, …N. -the different years when replacement is considered (ie age of machine)
T = Tractor cost, ₦/h
U_m = The least cost to get to state m by remaining in operation via replacing or keeping the item
V = Discount factor $(1-i)^{-k}$
W = Amount of material to be transported, Tonnes
w = Effective width of implement, m
Y = Yield of crop, Tonnes/ha
yV = Value of crop, ₦/Tonnes
Z = Schedule constant, 2 for premature or delayed schedules and 4 for balanced schedules
Ω = Annual timeliness cost, ₦/h
λ = The probability of a working day, decimal.

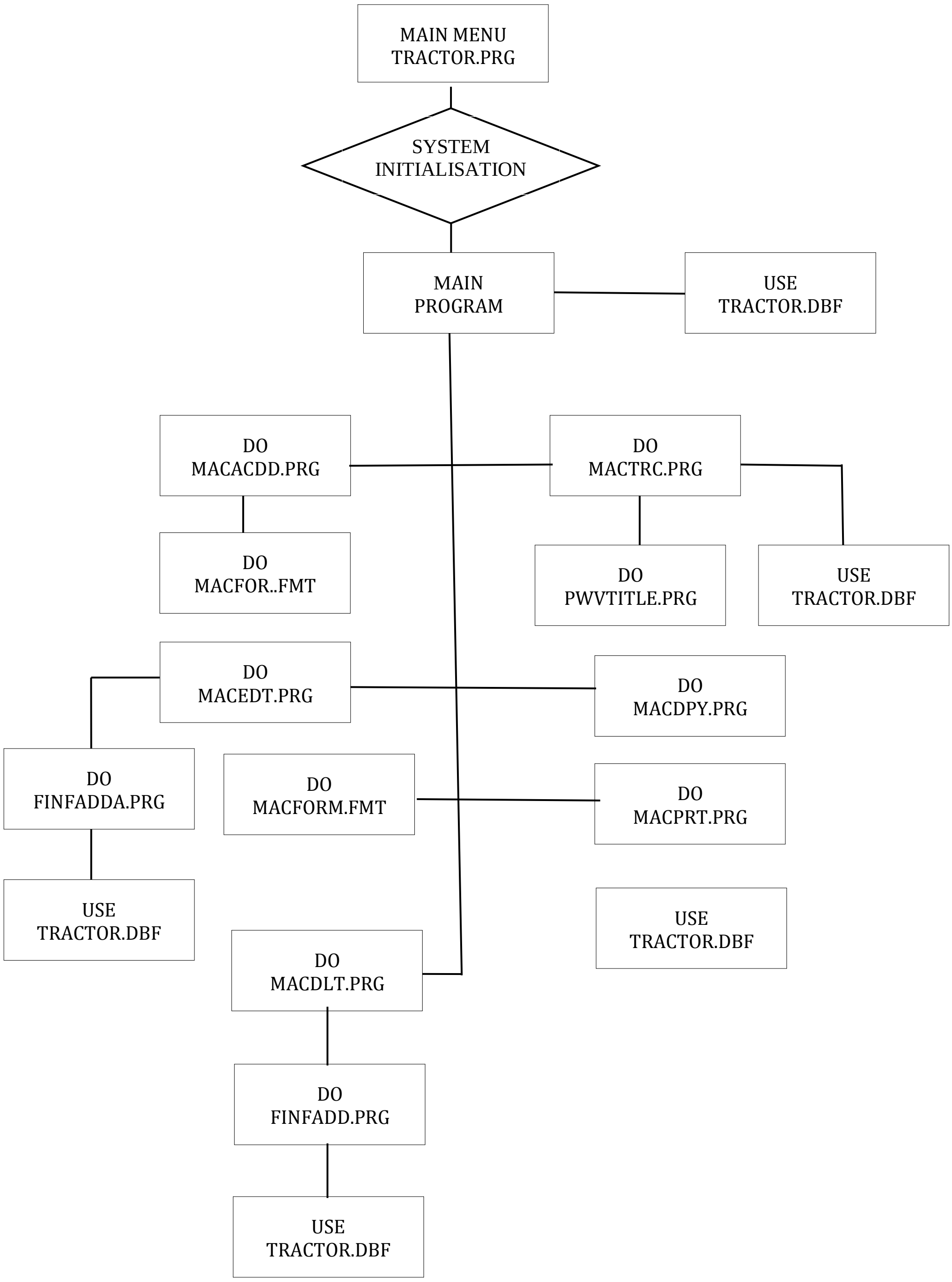
PROGRAM MODULES

The flowcharts for the main menu and some of the sub-programs are presented in the appendix. The functions of the menu and subprograms are presented as follows:

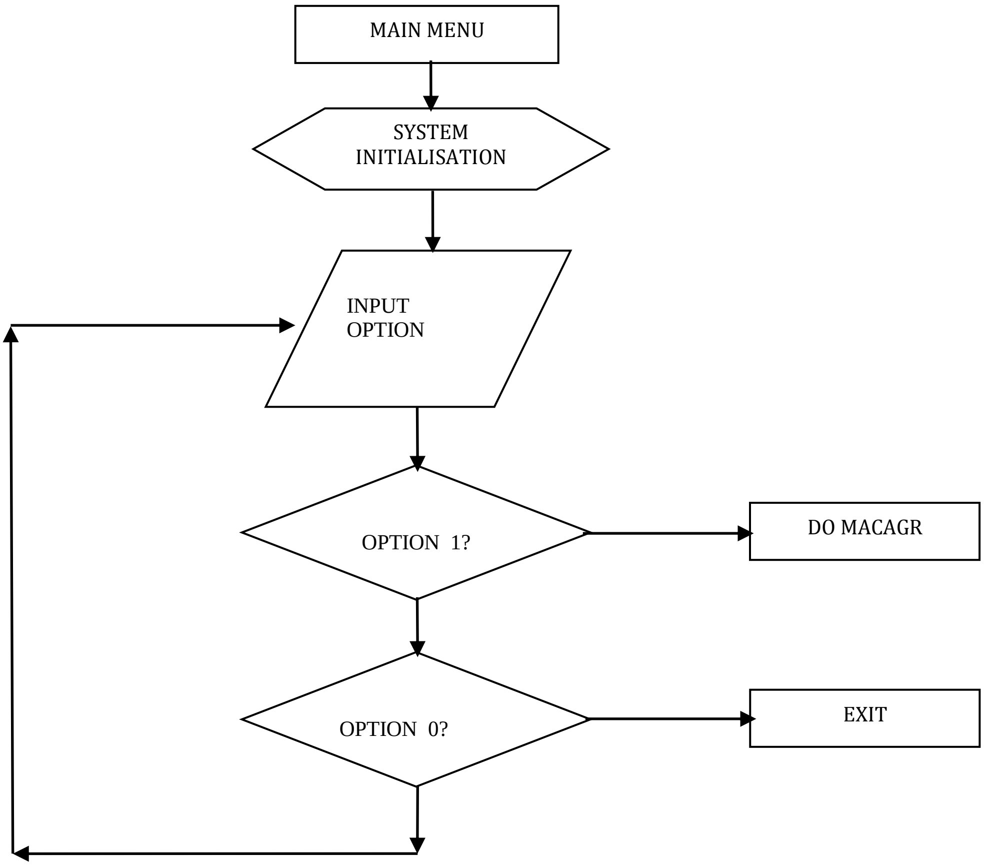
Main Menu:

TRACTOR.PRG - Displays the main screen design where user enters option “1” to begin using the program or option “0” to exit the program.
MACAGR.PRG - This also displays another menu through which the user can perform the main activities of the program such as add to disbursement record, edit or remove existing disbursement record, display or print existing record, and computation.
MACADD.PRG - Performs the addition of a new record.
MACEDT.PRG - Performs the editing of record.
MACDLT.PRG - Does the work of removing a record.
MACDPY.PRG - Displays an existing record.
MACPRT.PRG - Produces a hardcopy disbursement record.
MACTRC.PRG - Displays some output headlines and performs calculation.
PWVTITLE.PRG - Displays the calculated value’s column title.
FINFADDA.PRG - This module is used to search for any disbursement record.
TRACTOR.DBF - The database file that holds the disbursement record.
MACFORM.FMT - Special module that displays the disbursement database record form.

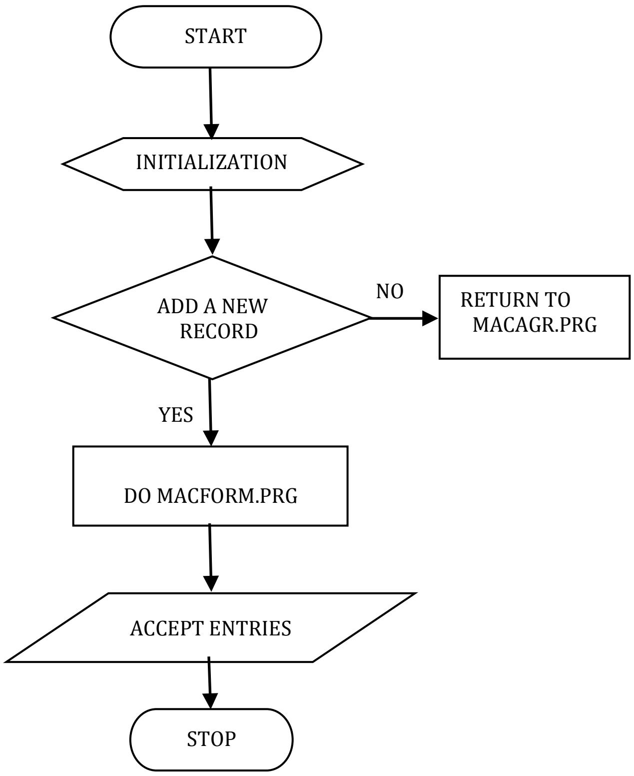
Appendices



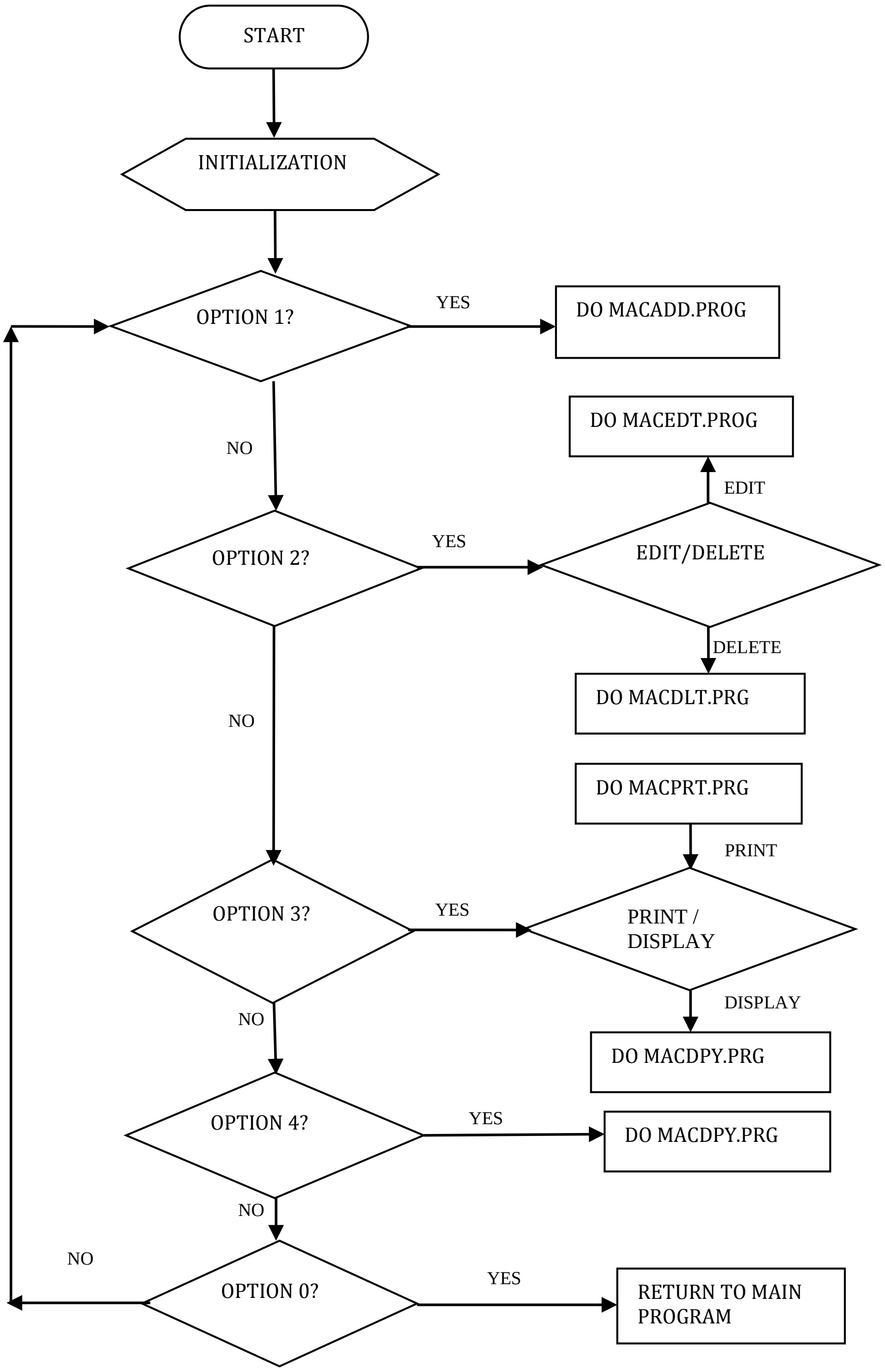
Appendix A: System flowchart of the replacement and maintenance model



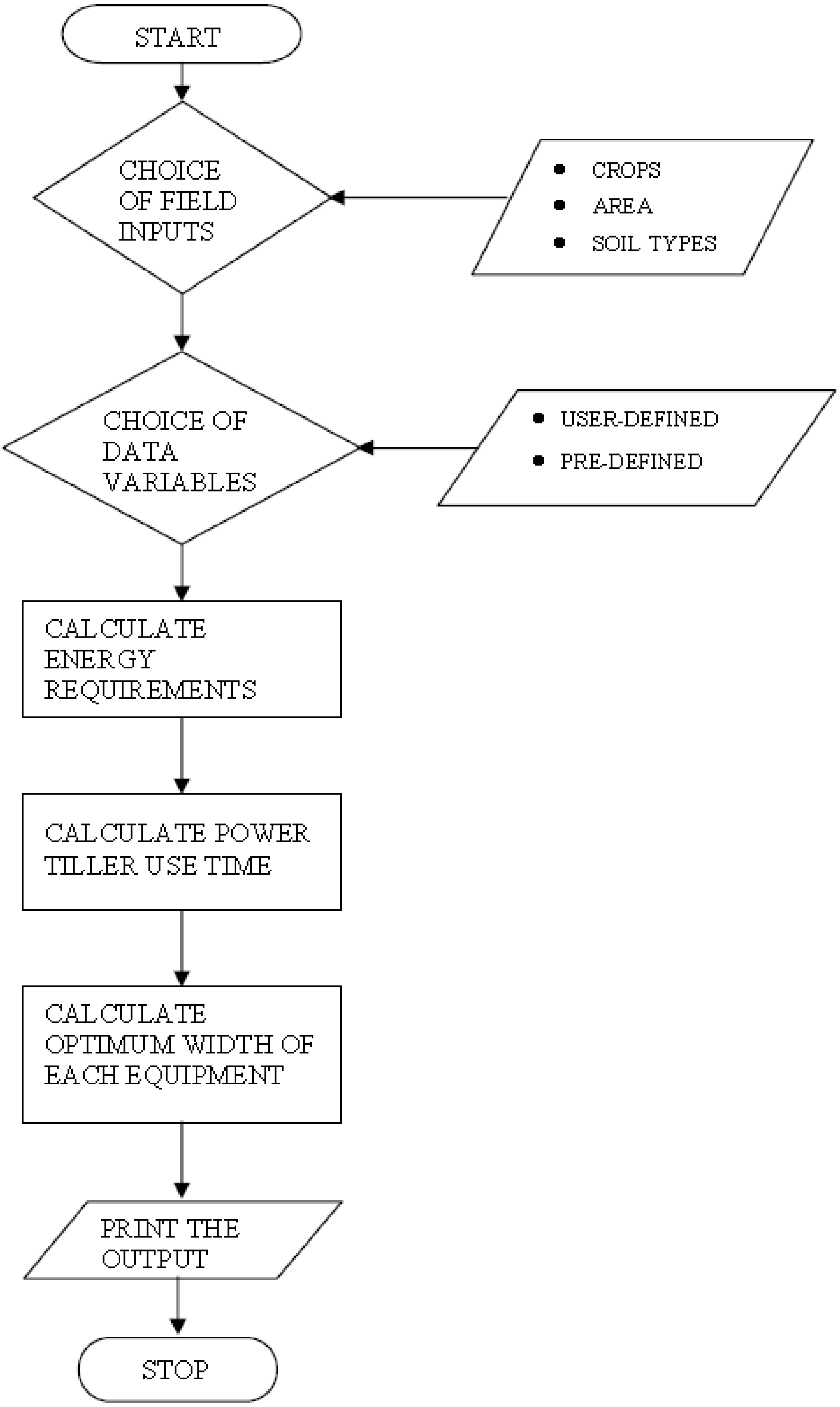
Appendix B: Main menu flow chart



Appendix C: Add record sub program –MACADD.PRG



Appendix D: Edit-Delete-Print-Display Programme Flow Chart



Appendix E: System flow chart for computation of optimum width of equipment
Source: [1]

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