INTEGRATING GIS, TABU SEARCH, AND AGRONOMIC SCHEDULING FOR OPTIMIZING AGRICULTURAL MACHINERY UTILIZATION IN ETHIOPIAN FARMING SYSTEMS: A CASE STUDY OF HITOSA FARMERS' COOPERATIVE UNION

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SIRNA QONNAA ETIYOOPHIYAA KEESSATTI ITTI FAYYADAMA MASHIINARII QONNAA FAYADUUF GIS, BARBAACHI TABU, FI SAGANTAA AGRONOMIC WAL QABACHUU: QORANNOO HAALA WALDAA TUMSA QONNAA HIXOOSA

Siraj K. BUSSE[1*], Rediat G. ABEYU[2], Sintayehu L. ZELEKE[3], Dejene G. GADISA[1]
[1]Adama Science and Technology University, College of Mechanical, Chemical, and Materials Engineering, Adama, Ethiopia
[2] Ministry of Agriculture, Addis Ababa, Ethiopia; [3] Melba Publishing and Printing, Dukam, Ethiopia
**Corresponding Author Telephone: +251921484487, E-mails: siraj.kedir@astu.edu.et; siraj.buse@gmail.com*

DOI: https://doi.org/10.35633/inmateh-78-36

Keywords: *Agricultural mechanization, GIS-based optimization, Tabu Search, Machinery scheduling, Fuel efficiency, Cooperative fleet management*

ABSTRACT

Smallholder mechanization in Ethiopia remains low and operationally inefficient, constraining productivity and food security. This study develops and tests a data-driven framework that integrates GIS, Tabu Search, and agronomic scheduling to optimize machinery utilization for the Hitosa Farmers' Cooperative Union. A mixed-methods design combined a full census of the union's fleet, GPS field tracking, climate and land-use GIS analysis, CROPWAT-based crop calendars, and time-motion measurements. Optimization as performed using Tabu Search and integer/nonlinear programming implemented in MATLAB and ArcGIS to minimize total travel distance, balance workload, and reduce total operational cost. Spatially differentiated scheduling and route optimization reduced machinery idle time by 30% and produced average fuel savings of 11.28% (23.34% in Hetosa Woreda). According to the assessment, there were 1,230–1,300 hours of inefficient travel and 123,852 ETB in direct labor losses; the estimated revenue losses from combine harvesting and foregone tillage were 2.16 million ETB and 3.33 million ETB, respectively. According to a geospatial demand analysis, 117 tractors (130 HP) or 94 tractors (150 HP) were needed for seedbed preparation, and 137 combine harvesters (220 HP) were estimated to be needed throughout the union's service area. While prioritizing equipment allocation based on crop timeliness and terrain, the updated scheduling and routing decreased the overall distance variance between machines. Cooperative mechanization yields quantifiable economic and environmental benefits when GIS, optimization algorithms, and agronomic calendars are integrated. GPS-enabled devices, centralized logistics, and scheduled fleet replacement are among the priorities; cooperative systems can be compared using the suggested framework to improve service sustainability, dependability, and cost-effectiveness.

ABSTRACT IN AFAAN OROMO

*Mekaanizeeshiinii qonnaan bultoota xixiqqaa Itoophiyaa keessatti yeroo ammaa bu'a qabeessa miti, kunis oomisha fi nageenya nyaataa irratti dhiibbaa guddaa fida. Qorannoon kun haala Waldaa Qonnaan Bultoota Hitosa irratti xiyyeeffachuun, **GIS, Tabu Search**, fi **tarsimoo qonnaa** walitti makuun meeshaalee qonnaa itti fayyadamuu fooyyessuuf qophaa'e. Qorannoon kun mala qorannoo walmakaa fayyadamuun, lakkoofsa guutuu meeshaalee waldaa, hordoffii lafa irratti GPS, qorannoo qilleensa fi fayyadama lafa (GIS analysis), karoora oomisha (CROPWAT), fi safartuu hojii (time-motion) of keessatti qabata. Fooyya'insi kun **Tabu Search** fi **integer/nonlinear programming** MATLAB fi ArcGIS irratti hojiirra oolee, kaayyoon isaa fageenya imalaa xiqqeessuu, ulfina hojii walqixa qooduu fi baasii hojii guutuu hir'isuu ture. Tarsimoon haaraan yeroo meeshaaleen hin hojjenne dhibbeentaa 30% hir'ise, akkasumas **balaqqee boba'aa giddu galeessa 11.28%** (gara 23.34% tti Hetosa keessatti) akka ta'e mirkaneesse. Qorannoon akka agarsiisutti, sa'aatii hojii bu'a qabeessa hin taane 1,230–1,300 fi miidhaan mindaa hojii to'ataa qarshii **123,852 ETB** dha. Dabalataan, badhaadhinni dhabame oomisha walitti qabuu irraa **2.16 miliyoona ETB** fi qotannoo dhabameen **3.33 miliyoona ETB** ta'uu ittiin tilmaamame. Qorannoon geospatial agarsiise traktorii 117 (130 HP) yookaan 94 (150 HP) fi **combine harvester 137 (220 HP)** guutuu daangaa tajaajila waldaa keessatti barbaachisu akka ta'e. Tarsimoon haaraan oomisha yeroo fi haala lafa irratti hundaa'ee meeshaalee qooduun garaagarummaa imalaa xiqqeesse. Waliigaltee **GIS, algoritiimii fooyya'insaa fi karoora qonnaa** waliin fayyadamuun bu'aa dinagdee fi naannoo argamsiisa. Kana malees, fayyadama **GPS**, tajaajila geejjibaa walitti qabamee fi fleet yeroo murtaa'eetti jijjiiruu dursa kennee, tajaajila itti fufaa, amanamaa fi baasii gadi bu'e mirkaneessa.*

INTRODUCTION

Ethiopia's population is predicted to increase from 126.5 million in 2023 to 143 million by 2037 (African Development Bank Group, 2024; Central Statistical Agency, 2021). One of the biggest challenges is ensuring food security for its quickly growing population. Agriculture, a vital sector that contributes more than 34% of the GDP, employs about 71% of the workforce *(Agricultural Transformation Agency, 2018; Diriba, 2022; FAO et al, 2024; Ministry of Agriculture, 2022*). The lack of mechanization and reliance on traditional farming methods are the main causes of the agricultural sector's low productivity, despite its significance. Mechanized equipment is used in just 0.7% of agricultural production, mostly for the production of wheat *(Ministry of Agriculture, 2022*). This low rate of mechanization hinders the sector's ability to meet the demands of food production, particularly as the population grows.

Access to mechanized equipment is a major barrier for Ethiopia's smallholder farmers, who make up a sizable portion of the agricultural workforce. The main obstacles to the widespread adoption of mechanization are high machinery costs, poor distribution infrastructure, and restricted credit availability (*Ministry of Agriculture, 2022*). Physical optimization to improve scale and efficiency has historically propelled the global evolution of agricultural machinery (*Bantelay et al., 2020; Bochtis et al., 2014; Bratoev, 2025; Deribe et al., 2022; MoANR & ATA, 2014; Sidhu, 2021*). However, biological and environmental factors like soil compaction frequently limit the additional benefits of larger machinery *(Gubiani et al., 2024; Seyoum et al., 2013; Shaheb, 2021)*.

Current research has focused on increasing the productivity of complex machinery systems through the use of advanced technologies such as actuation, sensing, and information and communication technologies (Africa Union, 2019; Gamage et al., 2024; Kalfas et al., 2024; Satyam et al., 2024; Zerssa, 2021). However, efficient machinery management is necessary for the successful application of farm mechanization, and cooperative farming systems face this difficulty. For many years, the primary suppliers of mechanization services in Ethiopia have been groups such as the Hitosa Farmers' Cooperative Union *(Cherkos & Olaniyan, 2024; Koroso, 2016)*. However, these cooperatives typically lack the contemporary management tools required for operational optimization and data-driven decision-making. Hitosa Union preliminary assessments show that poor scheduling, inefficient resource allocation, and a lack of systematic data recording limit the management of machinery, resulting in long-term problems with underutilized machinery, delayed services, and increased operating costs.

The potential of agricultural mechanization and its cost-effective implementation are still very far apart, largely because there aren't any research-based frameworks that employ state-of-the-art optimization techniques to address current operational inefficiencies. To bridge this gap, the current study employs operational research methodologies to enhance the use of agricultural machinery by the Hitosa Farmers' Cooperative Union.

MATERIALS AND METHODS

Study area description

The study's operational area was the Hitosa Farmers' Cooperative Union, a crucial center for agricultural services in Ethiopia's Arsi Zone in the Oromia Region. The woredas of Hitosa, Dodota, Sire, Lume, Zeway Dugda, Tiyo, and Munessa are home to the union's seven main cooperatives. With elevations ranging from 1,500 meters to the 4,170-meter summit of Mount Chilalo, the terrain is varied.

According to the FAO soil classification (*FAO, 2006*), the major soil types include Vertisols in Dodota and Zeway Dugda, Nitisols in Hetosa and Lode Hetosa, Luvisols in Sire, and Cambisols and Andosols in Tiyo and Munisa. These soils vary in drainage, fertility, and workability, requiring site-specific field management.

Historical meteorological data from six stations Melkasa, Huruta, Kulumsa, Assela, Ogolocho, and Degaga were used to characterize rainfall patterns and soil moisture dynamics across the woredas. The area experiences a distinct dry season (November-January), short rains (February and October), moderate rainfall (March-June), and a main rainy season (July-September) (Teshome Game, 2015). Seasonal variations in soil moisture and rainfall distribution were considered in scheduling field experiments and selecting suitable periods for tillage, planting, and machinery performance evaluation.

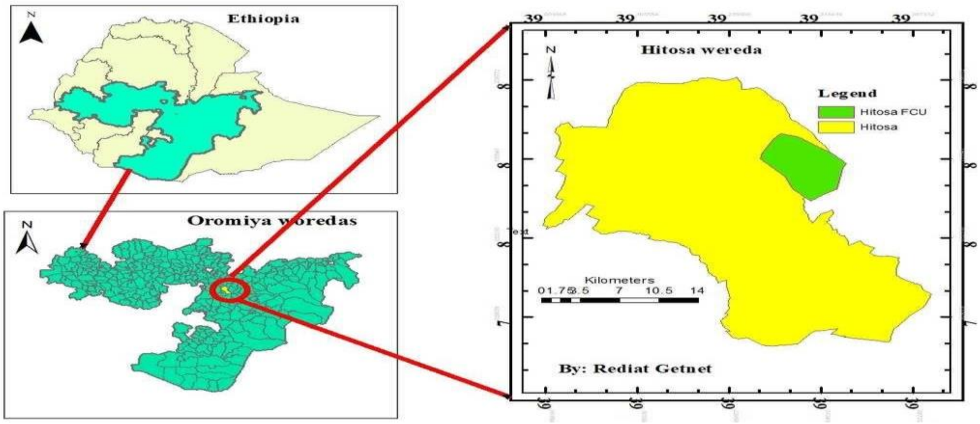

Fig. 1 - Maps of Hetosa Woreda, Oromiya Region

Sampling and data collection methods

A mixed-methods approach was employed to evaluate the use of machinery. Purposive sampling was used to choose key informants from the departments of mechanization, finance, and agronomy, and a thorough inventory of all union machinery assets was carried out. During the data collection process, triangulation was used to guarantee validity. Stakeholder surveys, field observations (including GPS tracking and time-motion studies), and structured interviews were used to collect primary data in order to measure performance indicators such as field capacity and fuel consumption.

Optimization Model for Agricultural Machinery Utilization

To optimize the use of agricultural machinery and analyze performance under varying field conditions, this study employed modelling and simulation techniques (Fig. 2).

Capacity and cost of farm machinery

Equations 1 and 2 provide the theoretical capacity and effective field capacity, which are part of the tractor's mathematical modelling *(Chowdhury et al., 2025; Sarker, 2019)*.

$$Theoretical\ Capacity\ (Ct) \qquad \mathrm{C_t} = \frac{\mathrm{S} * \mathrm{W}}{10} \tag{1}$$

$$Effective\ field\ capacity\ (Ce) \qquad \mathrm{C_e} = \frac{\mathrm{S} * \mathrm{W} * \mathrm{E}_f}{10} \tag{2}$$

where W is the machine's rated width in meters, $\mathrm{E_f}$ field efficiency in fractions, and S is the machine's average speed in kilometers per hour.

Equation 3 from the model proposed by *Chowdhury et al., (2025*) was used to integrate fixed and variable costs in order to determine the total annual cost of tractor operation (Ac):

$$A_c = F_c P_t + A_t (RM + L + O + F + T_c) \tag{3}$$

$$A_c = F_c P_t + (Field\ hours)\ (L + timeliness\ cost) + (transport\ hours)\ (Lt) \tag{4}$$

where P_t is the tractor purchase price, in rupees, and F_c is the annual fixed costs, which is a fraction of the purchase price. A_t represents the annual tractor use (h/yr); RM denotes repair and maintenance costs, which are ETB/h; L is the labor cost for field operations, which are Rs/h; T_c represents timeliness costs (ETB/h); O is the oil cost, ETB/h; and F is the fuel cost, ETB/h. The cropped area is denoted by A, the energy required to cover this area by E, the field worker's wage (ETB/h) by L, and the labor cost for transportation is denoted by Lt.

The optimal tractor size was defined as the unit capable of performing all required operations at the minimum total cost. The annual hours of work for each tractor operation class were determined and satisfied the minimum cost condition defined by the second derivative test in Equation 5 (*Islam et al., 2022*):

$$F\frac{\partial^2 (Ac)}{\partial {R_p}^2} = \frac{2\ C1\ Eo\ (L + Tc)}{\left(R_p\right)^3} + \frac{2\ C2\ \ Et\ \ Lt}{\left(R_p\right)^3} \tag{5}$$

where $C1$ is the ratio of A and r. A is Area; r is Ratio of drawbar power to rated engine power for drawbar loads and ratio of PTO power to rated engine power for PTO loads; Eo is the Energy required per unit area; R_p is Rated power; Et is energy required by the tractor for transportation (0.53 (HP/km)), $C2$ is the constant of transportation time.

The timeliness of a field operation must be considered in the optimum power required of a tractor. The total timeliness cost for an operation depends on the scheduling of operations (delayed, premature, and balanced). So, the total timeliness cost (Tc) can be estimated as equation 6 (*Islam et al., 2022*):

$$T_c = \frac{K * Y * V * A^2}{X * U * Z} \tag{6}$$

where K is the Timeliness loss factor, Y is Crop yield, V is the Value of the crop in Rs/t, A is Total area under crop, ha, U is the Ratio of total working days to total days, fraction; Z is Effective machine capacity, ha/day; X is 2 for premature or delayed scheduling and for balanced scheduling.

Cost of Farm Machinery

Both fixed and variable components were used to determine the overall cost of owning and operating machinery (*Deribe et al., 2022; Islam et al., 2020; McFadden, 2023*). Depreciation, interest, taxes, insurance, and housing were examples of fixed costs that were unaffected by usage. According to *Busse et al., (2025)*, variable costs included labor, fuel, lubrication, and repair and maintenance. These costs were proportionate to usage. To create operational baselines, these elements were measured for every piece of equipment.

A. Fixed costs

Depreciation, interest on investments, insurance and shelter, and taxes are among the fixed costs of farm equipment. Depreciation, which is determined using the straight-line method (Equation 7), is the yearly decrease in the value of machinery as a result of age and use. The cost of capital invested in machinery is reflected in investment interest, which is calculated using the average investment and the current interest rate (Equation 8). Equation 9 is used to calculate annual taxes, which are normally 1-2% of the purchase price (*Islam et al., 2022*), while insurance and housing costs are estimated to be 2% of the annual purchase price.

$$D = \frac{C - S}{L * H} \tag{7}$$

$$I = \frac{C + S}{2} * \frac{i}{H} \tag{8}$$

$$T = \left[\frac{C}{2}\right] \times 0.55 \times TR \tag{9}$$

where: D - depreciation per hour; I - annual interest (ETB/year); T - annual tax (ETB); C - capital investment (ETB); S - salvage value (10% of C); L - machine life (years); H - annual working hours; I - interest rate (%); and TR; tax rate.

B. Variable costs

Institutional records and empirical field measurements were used to quantify variable costs. During operations, fuel consumption was directly measured through GPS tracking and tank refills. The union's historical operational data (2018/19–2024/25) was used to calculate repair and maintenance costs. Payroll records were used to determine labor costs, which were then proportionately allocated to the use of machinery. According to Equation 10, lubricant expenses were calculated to be 15% of fuel expenses *(Islam et al., 2022; McFadden, 2023; Zhu et al., 2022*).

$$Lubrication\ cost\ per\ hour = fuel\ cost\ per\ hour * 0.15 \tag{10}$$

Optimization Model for Agricultural Machinery Scheduling

For the Hetosa Farmers' Cooperative Union, this study created a scheduling model that optimizes machinery allocation to reduce operating costs (*Sun et al., 2023*). The model solves the route optimization problem using the Integer Nonlinear Programming (INLP) and Tabu Search algorithms (*Niroumandrad et al., 2024; Serna et al., 2021)*. Equation 11 (*Chavdar et al., 2025; Jwo et al., 2023*) illustrates how the objective function balances inter-machine workload across the union's scattered fields while minimizing the total distance travelled by the fleet of diverse machinery:

$$f = \min \left(w * \sum_{m=1}^{M} \sum_{i=0}^{H} \sum_{j \neq i, j=0}^{H} (d_{ij} x_{ijm}/v) + \mathrm{r} * {}_{m=1}^{M}\beta \sum_{i=0}^{H} \sum_{j \neq i, j=0}^{H} (d_{ij} x_{ijm}/v)\right) \tag{11}$$

The optimization model minimized a weighted objective function combining total travel distance and distance variance across the machinery fleet. Travel time between fields was calculated as the quotient of distance and constant speed (Equation 12). Each machine's total distance was computed as the sum of all inter-field segments traversed (Equation 13), subject to the constraint that all routes must originate and terminate at the central depot (Equation 14) (*Mishkhozhev et al., 2020; Zhu et al., 2022*).

$$t_{ij} = d_{ij}/v, \forall i,j \in \{0,1,\cdots,H\}, i \neq j \tag{12}$$

$$D_m = \sum_{i=0}^{N} \sum_{j=0,j\neq i}^{N} x_{ijm} d_{ij}, \forall m \in \{1,2,\cdots,M\} \tag{13}$$

$$\mathrm{So} = \mathrm{S}_{H+1} \tag{14}$$

where:

M	Total number of available machines
H	Total number of fields to be served
$S_i, (i=1,2...H)$	Each field is labelled 1 to H, with the depot labelled as 0 and H+1
H_o	Agricultural machine depot
d_{ij}	Distance between the two fields i and j
V	Constant speed of machines
t_{ij}	Travel time of the machine between the two fields i and j
D_m	Total distances that machine m travels
W	The weight of the total travel distances of all machines
x_{ijm}	1 if machine m travels from field i to field j, otherwise 0
y_{mi}	1 if machine m serves field i, otherwise 0

Mathematical modelling for the cost of machinery

A composite cost model was formulated to minimize total operational expenses by integrating fixed and variable cost components. A mathematical model was developed to minimize the total annual cost of the agricultural machinery system, which was formulated as the sum of fixed, variable, and time loss costs (*Chavdar et al., 2025; Deribe et al., 2022; Mishkhozhev et al., 2020; Yousif et al., 2013*). Fixed costs were annualized using a dynamic depreciation method, while variable costs were calculated for each machinery unit based on operation time, the number of units deployed, and daily rates, with distinct values applied for each specific operation and growth stage (equations 15-18).

$$Operational\ cost, \qquad Min(Total_{cost}) = Min(Fixed_{cost} + Variable_{cost}) \tag{15}$$

Annual fixed cost,

$$C_{ft} = \sum_{j=j_1}^{j_m} \left\{ \left[\left[P_{tj}(1+I)^{L_{tj}} - P_{tj}S_{rt} \right] \times \frac{I}{(1+I)^{L_{tj}} - 1} + \alpha P_{tj} \right] X_j \right\} \tag{16}$$

$$C_{fm} = \sum_{k=k_1}^{k_m} \left\{ \left[\left[P_{mk}(1+I)^{L_{mk}} - P_{mk}S_{rm} \right] \times \frac{I}{(1+I)^{L_{mk}} - 1} + \alpha P_{mk} \right] X_k \right\} \tag{17}$$

Annual Variable Cost

$$C_{fm} = \textstyle\sum_{k=k_1}^{k_m} \left\{ \left[\left[P_{mk}(1+I)^{L_{mk}} - P_{mk}S_{rm} \right] \times \frac{I}{(1+I)^{L_{mk}-1}} + \alpha P_{mk} \right] X_k \right\} \tag{18}$$

where: C_{ft} is the annual fixed cost of the tractor; j_1 and j_m denote the first and last tractor types; P_{tj} is the purchase price of the j-th tractor; I is the interest rate; L_{tj} is the depreciation period (years); S_{rt} is the salvage value rate; and X_j is the number of tractors required annually. C_{fm} is the annual fixed cost of implements; k_1 and k_m represent the first and last implement types; P_m is the purchase price of the k-th implement; L_{mk} is its depreciation period; S_{rm} is the salvage value rate; and X_k is the number of implements needed yearly.

Constraints of the objective function

The allocation of both tractors and implements is constrained by ensuring the total quantity of each type does not exceed the maximum number deployed in any single agricultural stage, as defined by Equations 19 and 20, respectively (*Chavdar et al., 2025; Deribe et al., 2022; Mishkhozhev et al., 2020; Yousif et al., 2013*). The number of machinery units required for key operations is bounded by fixed start and end dates, with the operation time for each crop assumed constant.

$$X_j - \underset{i}{\forall} \left\{ \sum_{k=k_1}^{k_m} \sum_{l=l_1}^{l_m} X_{ijkl} \right\} \geq 0 \tag{19}$$

$$X_k - \underset{i}{\forall} \left\{ \textstyle\sum_{j=j_1}^{j_m} \sum_{l=l_1}^{l_m} X_{ijkl} \right\} \geq 0 \tag{20}$$

where:

X_j represent the number of tractors of type j; X_k is the number of implements of type k; and X_{ijkl} is the allocation of a machinery unit composed of tractor type j and implement type k to perform operation iii on crop l. The indices i, j, k, and l refer to the agricultural operation (growth stage), tractor type, implement type, and crop type, respectively.

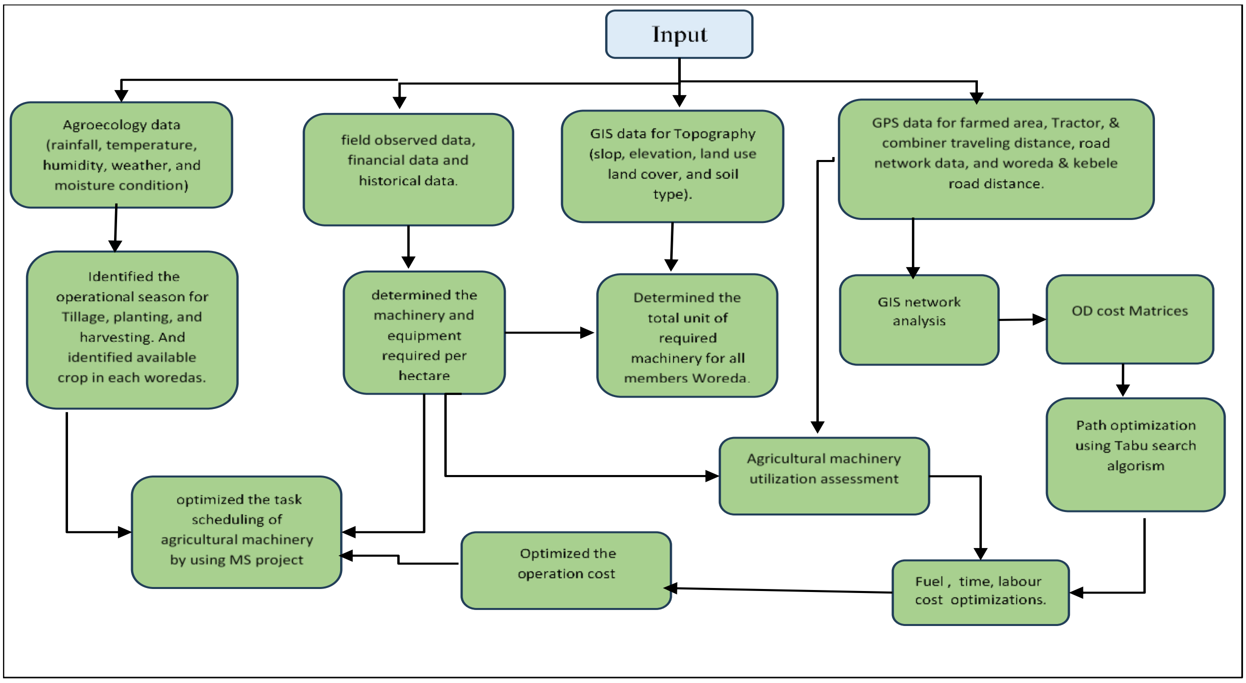

Fig. 2 - Agricultural machinery utilization optimization workflow

In order to determine crop water requirements, the study used CROPWAT 8 software to estimate evapotranspiration.

Data Analysis

Both quantitative and qualitative data from primary and secondary sources were used in the study. The data were analyzed through tabular and graphical methods, alongside optimization models implemented via Tabu Search algorithms (*Niroumandrad et al., 2024; Serna et al., 2021; Yin et al., 2025*). To ascertain the ideal operational values, cost and schedule optimization were carried out using MATLAB and ARCGIS software, respectively (*Adesola et al., 2025*).

RESULTS

Agricultural machinery utilization assessment result

A mixed operational picture is revealed by the Hetosa Farmers' Cooperative Union assessment. Significant inefficiencies still exist even though the union uses a wide variety of branded equipment and keeps meticulous records of expenses and upkeep. Significant annual losses, operational inefficiencies from highly fragmented land plots (0.5-1 ha), and severe service delays brought on by inadequate machinery capacity across seven woredas are some of the main obstacles. These include a direct labor cost loss of 123,852 ETB and 1,230–1,300 hours of ineffective travel. Suboptimal utilization also leads to significant revenue losses, which are estimated to be 2,156,000 ETB from combine harvesting and 3,329,025 ETB from foregone tillage. The lack of digital scheduling systems, delayed input deliveries, the exclusion of important crops like teff and maize from some services, and the high cost of maintaining an aging fleet which is made worse by unpredictable weather and soil conditions all further impair operational capacity.

Machinery cost analysis

Depreciation is mostly determined by total engine hours rather than age alone, which causes heavy-duty equipment to lose value quickly, according to an analysis of the Hetosa Union's machinery costs for 2020–2024 (Table 1
).

The fixed cost calculation determined which pieces of equipment needed to be replaced right away because of high usage patterns that have made them economically obsolete. This financial analysis offers a clear foundation for future investment planning and fleet management optimization, especially when combined with comprehensive variable cost data.

Table 1

Average machinery cost analysis of 2020-2024

Tractor number	Machinery Age (year)	Fuel	Fuel cost	Lubrication cost	R & M	Labor	Operation cost
77	12	43.52	80281.52	24084.45	241425.1	103665.4	395520
1524	6	39.375	171489.9	51446.97	225943.1	127894.8	576806.3
76	12	42.84	79915.09	23974.52	245747.4	123405.2	473085
64	10	42.84	93109.17	27932.75	163810.8	114882.8	419778.4
63	10	42.84	100822.3	30246.7	99799.07	105312.6	336223.6
824	10	42.84	89421.59	26826.48	124304.1	107804.8	349599.8
823	10	42.84	68410.44	20523.13	196986.3	108914.6	314877.4

Optimization of operation costs

The study reduced the total and variable distances travelled in order to optimize machinery routing and minimize fuel and labor costs. This was accomplished by using ArcGIS to analyze the road network, which was digitized for the seven woredas and obtained from the Ethiopian Road Authority (Table **2**). Spatially explicit shortest paths were created using OD-cost matrix analysis, creating an ideal routing profile to direct effective machinery movement throughout the area. OD-cost matrix analysis was used to determine the shortest road or distance between two woredas.

Table 2

Shortest inter-woreda road distances from OD-cost matrix analysis

	Hetosa	*Sire*	*Lodo Hetosa*	*Tiyo*	*Munessa*	*Dodota*	*Dodota*
Hetosa	0.000	56.317	45.016	43.899	95.698	47.708	30.749
Sire	56.317	0.000	65.697	83.091	134.890	86.506	24.040
Lodo Hetosa	45.016	65.697	0.000	73.320	125.119	76.734	41.660
Tiyo	43.899	83.091	73.320	0.000	51.522	55.993	59.328
Munessa	95.698	134.890	125.119	51.522	0.000	80.347	111.176
Dodota	47.708	86.506	76.734	55.993	80.347	0.000	62.476
Dodota	30.749	24.040	41.660	59.328	111.176	62.476	0.000

Path optimization of agricultural machinery for the 7 Arsi Woredas

Path optimization for agricultural machinery operations across seven Arsi Woredas was performed using a Tabu search algorithm. Key operational parameters were incorporated into the model, including a tractor travel speed of 1.1 km/h, a plowing rate of 1.75 hectares/hour, and a fuel consumption rate ranging from 33 to 35 liters per hectare. Three tractor units were considered in the optimization process: two John Deere T2-130 tractors and one New Holland T1-150 tractor. The optimal route was derived with the objective of minimizing total travel distance. The results indicate that, compared with a random path strategy, the optimized routing approach yields significant efficiency improvements by effectively managing fuel consumption, reducing idle and downtime, and maximizing plowing area coverage.

Fuel savings achieved through optimized path following

The application of the Tabu Search algorithm for path optimization in Hitossa Town resulted in notable fuel savings for 130 HP and 150 HP tractors operating at a moderate load on level terrain. When compared to random operation patterns, Figure 3 shows how optimized routes greatly decreased the total travel distance. This cut resulted in a discernible drop in fuel consumption, with average savings of 11.28%. By lowering costs and increasing operational effectiveness, the optimized routes also reduced carbon emissions and tractor wear, improving economic and environmental performance.

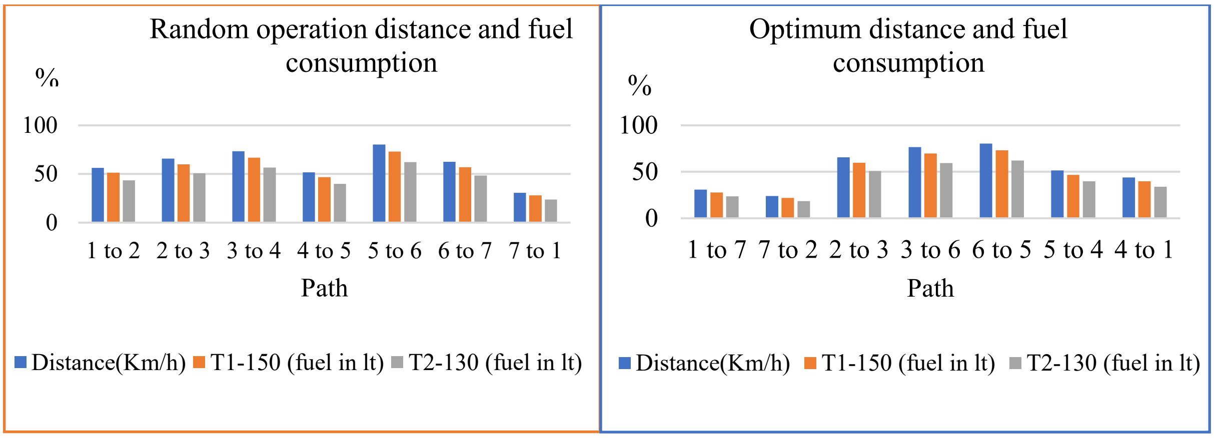

Fig. 3 - Distance covered and Fuel consumption for random and optimum operation

Machinery and equipment requirements per hectare

The machinery requirements of the Hetosa Farmers' Cooperative Union across its seven woredas were assessed using geospatial analysis (Table 3). For seedbed preparation, the analysis indicates a requirement of either 117 tractors rated at 130 hp or, alternatively, 94 tractors rated at 150 hp, the latter representing a more efficient option in terms of operational capacity. For harvesting operations, a total of 137 combine harvesters with an engine power of 220 hp are required. Among the assessed woredas, Munisa, Zuway Dugda, and Hetosa exhibited the highest machinery demand, followed by Lude Hetosa, Dodota, and Sire, while Tiyo Woreda showed the lowest demand. The results reveal substantial spatial variability in machinery requirements, highlighting imbalances in resource distribution and indicating significant potential for optimizing overall fleet size and allocation.

Table 3

Machinery capacity and usage

Machinery type	HP	Width	Ha/Hr.	Hr./day	working day/year
Tractor with disk plow	130	5 bottoms	1.3	10	120
Tractor with moldboard plow	150	6 bottoms	1.5	10	120
Combine Harvester	220	-	1.65	10	150
Tractor with row seeder 1	150	3m	3	10	120
Tractor with row seeder 2	130	2.6m	2.5	10	120

The machinery requirement per hectare for tillage operations varies substantially among the assessed woredas (Figure 4). Sire Woreda requires approximately 20 tractors rated at 130 hp or, alternatively, 18 tractors rated at 150 hp to meet its tillage demand. Lude Hetosa and Dodota fall within a medium requirement category, while Munisa, Zuway Dugda, and Hetosa Woredas exhibit the highest demand for tillage machinery.

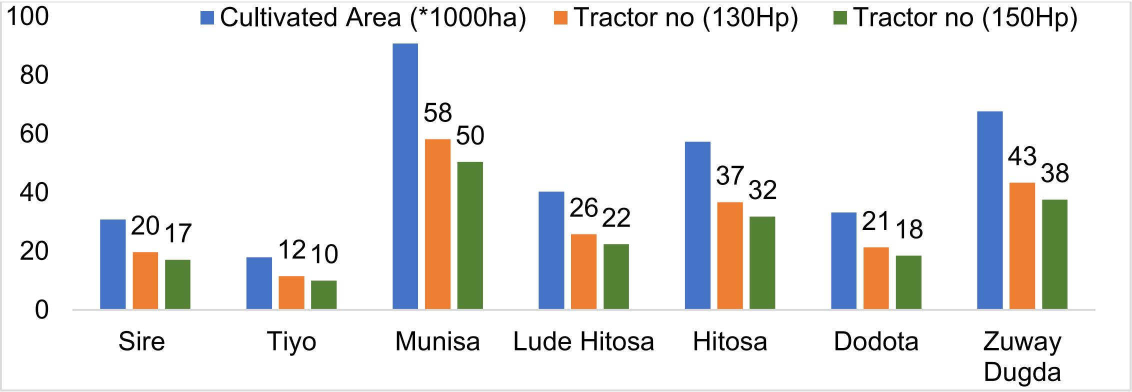

Fig. 4 - Area and machine requirement (5-Bottom disk plow)

The least amount of machinery is required by Tiyo Woreda. In order to effectively meet these demands, it is advised to use local service providers and optimize task scheduling in order to reduce the overall amount of machinery needed. Based on an analysis of the operational data, the projected machinery requirements for seedbed preparation differ considerably among the woredas.

For 130 HP tractors, Munisa has the highest need (31), followed by Zuway Dugda (23) and Hitosa (20). The requirements for Lude Hitosa (14), Sire (11), and Dodota (11) are moderate, while Tiyo has the lowest need (6). The pattern is identical for 150 HP tractors, with the highest needs in Munisa (26), Zuway Dugda (19), and Hitosa (16), and the lowest in Tiyo (4). This results in a total requirement of 117 tractors for 130 HP and 94 for 150 HP across all woredas as stated in Fig. 5.

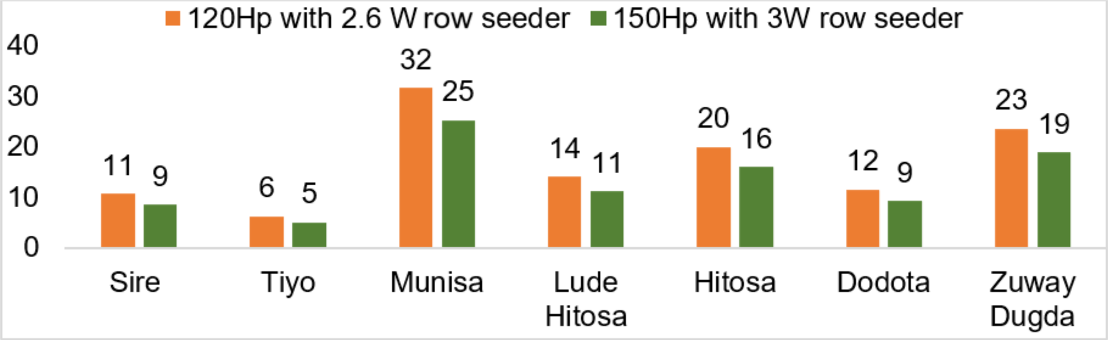

Fig. 5 - Machine requirements for seedbed preparation

According to Figure 6, the machinery requirement for harvesting operations varies significantly across the woredas. Munisa exhibits the highest demand, requiring 37 combine harvesters rated at 220 hp, followed by Zuway Dugda with 27 units and Hetosa with 23 units. Moderate requirements are observed in Lude Hetosa (16 units) and Dodota (13 units), whereas Sire and Tiyo show the lowest demand, requiring 12 and 7 combine harvesters, respectively.

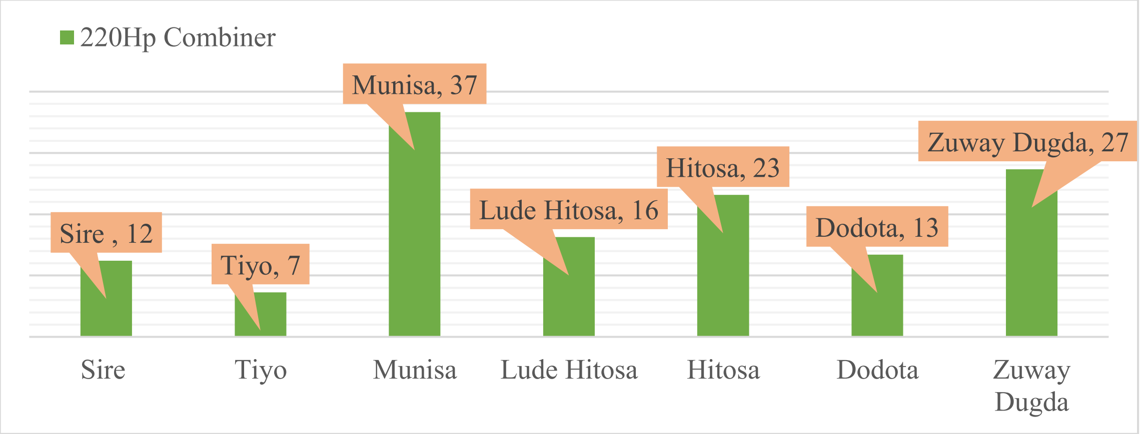

Fig. 6 - Combiner (220HP) requirements for harvesting operation

Overall, a total of 135 combine harvesters with 220 HP capacity are required across all woredas. This indicates that Munisa, Zuway Dugda, and Hitosa have the highest machinery demands, whereas Sire, Tiyo, and Dodota require relatively fewer machines for harvesting operations.

Task schedule for agricultural machinery

A thorough 934-day framework for mechanized farming was established for the Hetosa Farmers Co-operatives Union through the implementation of an optimized, multi-year operating schedule that integrated project management concepts with agricultural operational data. The primary seasonal operations, such as seedbed preparation (12.8-15.5 days), primary tillage (119-132.5 days), and harvesting (97-143.9 days), were methodically scheduled during the 319.4-day core implementation phase. To guarantee the dependability of the machinery, a strict, tiered maintenance schedule was implemented, consisting of daily (5-day), weekly (64-hour), monthly (576-hour), and annual (15-day) cycles. In addition to assigning specific personnel and equipment (tractors, combines, and operators) to each task, the schedule also carefully considered seasonal labor and overtime procedures to optimize resource use during periods of high demand. Additionally, to ensure operational oversight and continuity throughout the project lifecycle, administrative workflows for customer registration and reporting were seamlessly integrated.

CONCLUSIONS

This study evaluated machinery utilization within the Hetosa Farmers' Cooperative Union and developed a GIS-enabled Tabu Search optimization framework integrating GPS tracking data, crop calendars, time-motion analysis, and spatial demand clustering. Field measurements and a comprehensive fleet inventory were used to identify baseline operational inefficiencies. These included approximately 1,230–1,300 hours of inefficient travel per year, substantial downtime associated with an aging and heterogeneous machinery fleet, and an estimated annual economic impact of 5.48 million ETB, comprising 2.16 million ETB from foregone harvesting operations and 3.33 million ETB from foregone tillage activities.

Optimization experiments implemented using ArcGIS combined with the Tabu Search algorithm resulted in measurable operational improvements, including a 30% reduction in machine idle time and an average fuel consumption savings of 11.28% (in Hetosa Woreda, fuel savings increased to 23.34%).

Based on spatial demand translation, the peak-season fleet requirements within the union's service area were estimated at approximately 137 combine harvesters rated at 220 hp for harvesting operations and either 117 tractors rated at 130 hp or, alternatively, 94 tractors rated at 150 hp for seedbed preparation. The optimized scheduling scenarios improved operational timeliness and equity in equipment allocation by reducing total travel distance and minimizing variability in machine workloads across woredas. The results demonstrate that integrating combinatorial optimization techniques with agronomic calendars and geospatial demand mapping yields substantial operational and economic benefits for cooperative-based mechanization systems. In the short term, the highest-return interventions include implementing a digital, timetable-driven scheduling system, prioritizing the replacement of the most worn or inefficient machinery units, equipping high-utilization machines with GPS tracking, and adopting route-based dispatching strategies.

The establishment of centralized logistics facilities, such as fuel and spare-parts hubs, together with targeted fleet resizing based on quantified tractor and combine harvester requirements, represents a key medium-term priority. Over the longer term, the adoption of real-time scheduling systems, sensor-based condition monitoring, and phased financing mechanisms for fleet renewal is expected to deliver additional operational and economic benefits. When implemented alongside institutional reforms and capacity-building initiatives, the proposed framework can substantially improve service reliability, reduce operating costs and fuel consumption, and mitigate unnecessary asset depreciation. Moreover, the approach is scalable and applicable to similar cooperative-based mechanization systems.

ACKNOWLEDGEMENT

The authors acknowledge Adama Science and Technology University for financial and in-kind support during the research work of this study.

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