The model of vehicle optimum quantity for grain crop harvesting under the conditions of farming in Poltava region

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Abstract. The previously developed optimization model for determining the required number of vehicles as part of the harvest transportation complex during grain crop harvesting for the conditions of grain farming in Poltava region has been applied. A computational methodology was developed to determine the design parameters depending on the farm conditions included in the expression for the target function of the optimization model constructed, namely, average number of arrival rate per time and waiting time in queue (excludes service time) for each individual customer. Using the queueing theory methods, a ratio of the number of harvesting and transport equipment in the harvest transportation complex composition was found, which provides the minimum total costs (corresponding to the target function of the previously proposed model), which are due to the downtime of combine harvesters and the cost of vehicle maintaining. It has been established that with the increase in the vehicle number, the total costs of downtime of combine harvesters and vehicles decrease at first and then increase.

1 Introduction

In agricultural production, the most labor-intensive and complex in terms of organizational, material and labour costs is the process of crops harvesting, including grain crops [1, 2]. Transportation costs take a significant place in the total amount of agricultural production costs – they make up to 15 to 40% of the cost of agricultural products [3]. Road transport is the main mode of transportation in agriculture, which accounts for up to 80% of the total volume of transportation. Road transport for grain is in demand in the agricultural regions of Ukraine, including Poltava region, for delivery of harvested wheat, rye, barley, legumes from fields to elevators and to other places of storage.

It is known that combine harvesting methods prevail in agricultural production [4, 5]. There are two methods of combine harvesting, namely, direct and separate harvesting. With massive maintenance on road transport, there are many processes involved, the examples of which can be specified in the process of accepting applications for cargo transportation,

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servicing the population with transport, vehixles running repairs, organizing technical assistance on the line, and much more [6-13].

In a mathematical model, a harvesting brigade can be represented as a system of mass service with anticipations, in which the servicing machine is a vehicle, and the served ones are combines.

Let us determine the number of vehicles in the harvest transportation complex based on the optimization model built using the queueing theory [14].

The model changes the vehicle number, which should be the criterion for minimizing the total costs of combines and vehicles downtime included in the harvesting complex for grain harvesting.

The calculated parameters depending on the conditions of the economy that are included in the expression for the target function of the optimization model constructed include average number of λ filled tankers (arrival rate) per hour and waiting time in queue W_q (excludes service time) for each individual customer, hours.

In the article, the composition of the source data to determine these calculation parameters is given. They are grouped together in three groups of parameters that characterize the conditions for grain harvesting in the given farming, determine the characteristics of the combine harvester, and the characteristics of the vehicle.

Substantiation of rational quantitative composition of machine complexes is the subject of numerous scientific works. With all their advantages, their general disadvantage is the complexity and calculations labour intensity [15]. It has been established [16] that the most rational number of machines in the complex is 8 to 16, and in the technological chain it is 3 to 5 units. The average value for the forest-steppe and more for the steppe zone is recommended [16]. With such a quantitative composition, the maximum productivity of machine tractor aggregates is reached at the least expenses for their servicing.

2 Model of determination of the vehicle number in the collecting-transportation complex

The following model is offered:

1. Select a model of a combine harvester from the number of available or based on comparative analysis of energy consumption of several models in the harvest.

Relative aggregate energy costs, MJ/ton, are expressed as the sum of the components:

$$\omega_C = \omega_K + \omega_{XX} + \omega_{Tn} + \omega_z + \omega_M \,, \tag{1}$$

where ω_K – relative energy consumption for moving self-propelled combines; ω_{XX} – relative energy consumption for idling; ω_{Tn} – relative energy consumption for the technological process; ω_z – relative energy costs of live labor of combiner; ω_M – relative energy consumption required for the production, repair and maintenance of machines.

Relative energy consumption for self-propelled combines, MJ/ton:

$$\omega_K = \frac{10^4 \cdot f_n \cdot g \cdot (m_a + m_o) \cdot (1 + \gamma_{xx})}{\eta_e \cdot \eta_T \cdot (1 - \eta_b) \cdot B \cdot A} \,, \tag{2}$$

where f_n – coefficient of rolling resistance in the movement of the machine ($f_n = 0.17$); g – acceleration of free fall, g = 9.81 m/sec^2; m_a – machine weight, kg; m_o –mass of grain transported in the harvester hopper during the operation, kg ($m_o \approx 0.5\varepsilon_0\gamma V_b$, where ε_0 is the coefficient taking into account the filling of the bunkers, $\varepsilon_0 \approx 0.9$ to 0.95, γ is the grain density, ton/m^3; V_b – the capacity of the bunker for grain, m^3); γ_{xx} – coefficient taking into account the proportion of idle passes ($\gamma_{xx} = 0.04$ to 0.25); η_e – effective efficiency factor of diesel engines ($\eta_e = 0.32$ to 0.36); η_T – coefficient of efficiency of mechanical transmission of energy from engine to propulsion ($\eta_T = 0.65$ to 0.85); η_b – coefficient of towing, for self-propelled combines, η_b = 0.04 to 0.06; B –width of the capture of the reaper, m; A – yield of grain, ton/hectare.

Relative energy consumption per idle of combines, MJ/ton:

$$\omega_{XX} = \frac{3,6 N_{XX} \cdot g_{on}}{\eta_e \cdot W_g}, \tag{3}$$

where N_{XX} is the relative power required to drive the working bodies at idling, $kW^x(kg/sec)^{-1}$ (for grain harvester combine N_{XX} = 2.7 (2.8) $kW^x(kg/sec)^{-1}$); g_{on} – nominal capacity of the combine harvester, kg/sec; W_g – hourly productivity of the combine, ton/hour.

Relative energy consumption per technological process, MJ/ton:

$$\omega_{Tn} = \frac{3,6 N_{Tn} \cdot g_{on}}{\eta_e \cdot Q_g}, \tag{4}$$

where N_{Tn} is the relative power required for the technological process, $kW^x(kg/sec)^{-1}$ (for grain harvester N_{Tn} = 7.6 $kW^x(kg/sec)^{-1}$); Q_g – milling of grain with a combine for an hour of work, ton/hour.

Relative energy costs of live labor combine harvesters, MJ/ton:

$$\omega_z = \frac{\alpha_z \cdot n_o}{W_g \cdot \tau}, \tag{5}$$

where α_z – energy consumption of live labor of combine harvesters, MJ/hour (according to FAO standards (UN Food and Agriculture Organization), equivalent α_z = 1.26 MJ/hour); n_o – number of hours of combine harvesters; τ – coefficient of use of working time change.

Relative energy consumption required for machine maintenance, MJ/ton:

$$\omega_M = \frac{\alpha_M \cdot M_M \cdot \left(a_a + a_p\right)}{T \cdot W_g \cdot \tau}, \tag{6}$$

where α_M is the energy equivalent which determines the energy consumption for the production of 1 kg of machine weight, MJ/kg (for tractors, self-propelled combines and cars, the energy coefficient α_M is taken to be 120 MJ/kg); M_M – constructive weight of the machine, kg; a_a, a_p – share of deductions from total energy consumption, respectively, for the production, repair and maintenance of machines (a_a = 0.111; a_p = 0.103); T – norm of annual loading of combine, hours.

Relative consumption of diesel fuel on aggregate energy consumption when harvesting 1 ton of grain by a combine, litre/ton:

$$q_T = \frac{\omega_C}{Q_T}, \tag{7}$$

where Q_T is the relative heat of combustion of diesel fuel, for calculations it is possible to take equal 35.9 MJ/liter (relative heat of combustion of diesel fuel – 42.7 MJ/kg [18]; according to the European standard EN-590 the average density of summer diesel fuel is 0.84 kg/litre).

Relative cost of diesel fuel for total energy consumption when harvesting 1 ton of grain by combine, UAH/ton:

$$C_T = q_T \cdot c_T, \tag{8}$$

where c_T – cost of a diesel fuel, UAH/litre.

2. Working speed of combine, km/hour [19]:

$$v_p = \frac{36 \cdot g_{on}}{B \cdot A \cdot \left(1 + \delta_c\right)}, \tag{9}$$

where g_{on} – nominal capacity of the threshing machine combine, kg/sec; B – width of the header capture, m (the short technical characteristic of the main models of combine harvesters is given in [9]); A – yield of grain crops, ton/hectare (shown in [16]); δ_c is the straw coefficient, the ratio of the mass of the nonzero mass of the crop (straw and half) to the mass of the grain (given in [19]).

3. Variable productivity of combine, hectare/shift [3]:

$$W_{ZM} = 0{,}1 \cdot B \cdot v_p \cdot T_{ZM} \cdot \tau \,, \tag{10}$$

where T_{ZM} – duration of shift (7 hours); τ – coefficient of time use shift (determined depending on the length of the race, see [16]).

4. Variable coefficient:

$$\alpha_{ZM} = \frac{T_{RD}}{T_{ZM}}, \tag{11}$$

where T_{RD} – duration of the working day (it is recommended to take T_{RD} = 10 hours on harvesting [21]).

5. In accordance with the given natural and production conditions of the economy set the required number of machine complexes and determine the number of n_K combine harvesters, units, by the formula:

$$n_K = \frac{F}{D \cdot W_{ZM} \cdot \alpha_{ZM} \cdot K_M \cdot K_G}, \tag{12}$$

where F is the harvest area of grains for the i-th complex, hectare; W_{ZM} – production rate per 7-hour shift, hectare [21]; α_{ZM} – coefficient of variability; K_M – coefficient taking into account meteorological conditions (in the autumn period take K_M = 0.7); K_G – coefficient of technical readiness (with a runtime of up to 15 days take K_G = 0.95, more than 15 days – K_G = 0.90).

There is also an dependence (an inverse dependence (12)) on determining the length of harvesting of cereals (the calendar harvest period), days:

$$D = \frac{F}{n_K \cdot W_{ZM} \cdot \alpha_{ZM} \cdot K_M \cdot K_G}, \tag{13}$$

where F – total harvest area of grain crop, hectare; n_K – total number of combine harvesters in the farm.

6. Choice of straw-harvesting machinery for variable productivity (see [16]).

7. Number of straw-cutting equipment:

$$n_c = \frac{F \cdot A \cdot \delta_c}{D \cdot W_{ZM}^c \cdot \alpha_{ZM} \cdot K_M \cdot K_G}, \tag{14}$$

where F – harvest area of grain crop, hectare; A – grain yield, ton/hectare; δ_c – coefficient of straw; W_{ZM}^c – variable productivity of a straw car, ton/shift.

8. Choosing a car to transport grain.

It is proposed to determine the estimated amount of grain bins that fit into the body of the used car:

$$n_b = \frac{q_a}{\gamma \cdot V_b}, \tag{15}$$

where q_a – nominal load-carrying capacity of the vehicle, ton; γ – grain density, ton/m^3; V_b – capacity of the hopper of the combine, m^3. The value n_b must be equal to or close to an integer. The capacity of the bunkers of the wide range of combine harvesters and the carrying capacity of the vehicles that correspond to their capacity is given in [16].

9. Time to fill the hopper of the combine with grain (loading), minutes [19]:

$$t_{ZK} = \frac{600 \cdot V_b \cdot \gamma}{B \cdot v_p \cdot A} \tag{16}$$

where v_p – operating speed of the combine, km/hour; B – working width of the combine harvester capture, m; A – grain yield, ton/hectare.

10. Duration of the vehicle's circulation, hours:

$$t_{ob} = t_P + t_{ZA} + t_G + t_D + t_V + t_X \ , \tag{17}$$

where t_P – time of the car in the field, hours; t_{ZA} – time of vehicle loading, hours; t_G – time of the car with a load, hours; t_D – time of documents processing, hours; t_V – time of unloading grain from the body of the car, hours; t_X – time of the car without cargo, hours.

11. Number of vehicles (cars) for maintenance of the machine complex:

$$n_a = \frac{n_K \cdot W_G \cdot A \cdot t_{ob}}{q_a \cdot \alpha_q \cdot K_G} \ , \tag{18}$$

where n_K – number of working combines, units; W_G – hourly productivity of combine, hectare/hour; A – yield of grain crops, ton/hectare; q_a – nominal load carrying capacity of a vehicle (vehicle), ton; α_q – coefficient of use of carrying capacity of a vehicle (vehicle); K_G – coefficient of technical readiness (with a duration of work up to 15 days take $K_G = 0.95$, more than 15 days - $K_G = 0.90$). It is recommended [12] to determine the number of vehicles (cars) separately for each type of transport, by its technical characteristics. To determine the calculated parameters λ and W_q, which are included in the expression of the target function of the developed optimization model, given in [14], the method shown in [16] can be used.

The value of λ corresponding to the number of harvester hoppers that will be filled in one hour depends on the loading time t_{ZK} and the discharge of the t_{VK} to the combine hopper:

$$\lambda = \frac{60 \cdot n_K}{t_{ZK} + t_{VK}} \ , \tag{19}$$

The duration of unloading of the hopper of the combine is determined depending on the density of the grain γ:

$$t_{VK} = \frac{V_b \cdot \gamma}{v_{rozv}} \tag{20}$$

For the system with expectation, the probability that the system is free, there are no applications for maintenance in the system, i. e. all service channels (cars) are idle, no combine is ready for unloading the grain:

$$P_0 = \left(\sum_{k=0}^{n} \frac{\rho^k}{k!} + \frac{\rho^{n+1}}{n!(n-\rho)} \right)^{-1} \ , \tag{21}$$

where n – the number of all channels of service in the system (the number of cars in the harvesting complex).

Determine the probability that the service occupied 1...n cars by the formula:

$$P_k = \frac{\rho^k}{k!} P_0 \tag{22}$$

Average queue length (number of combines waiting for bunker unloading):

$$L_q = \frac{\rho^{n+1} \cdot P_0}{n! \cdot n \cdot \left(1 - \dfrac{\rho}{n}\right)^2} \tag{23}$$

Average standby time of the combine, hours, which was queued at the start of service:

$$W_q = \frac{L_q}{\lambda} \tag{24}$$

As follows from the foregoing, calculations according to the proposed mathematical model indicate that, with the increase in the vehicle number, total costs from downtime of combines and vehicles are initially reduced and then increased [16]. That is, to determine the optimal value of the target function, it is expedient to erode the total costs received as per the number of vehicles, and with their increased number. The vehicle number for which the total costs will be minimal will be optimal for the considered harvesting complex.

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