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MODELING OF THE TRANSPORT AND PRODUCTION COMPLEX IN THE GROWING OF AGRICULTURAL CROPS, TAKING INTO ACCOUNT THE AVIATION COMPONENT

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Проведеними дослідженнями транспортно-технологічного процесу вирощування сільськогосподарських культур встановлено, що він являє собою складну динамічну систему. Доведено, що складність цієї системи полягає у наявності великої кількості різнорідних підсистем, у тому числі й транспортної, яка є важливою складовою для забезпечення вирощування сільськогосподарських культур. Завдяки системному підходу до дослідження транспортного забезпечення технологічного процесу вирощування сільськогосподарських культур стало можливим виявити функціональні особливості застосування наземних та авіаційних транспортних засобів. Встановлено властивості кожного етапу технологічного процесу вирощування та участі у ньому певного виду транспортних засобів.

Розроблено схему транспортного забезпечення технологічного процесу вирощування сільськогосподарських культур та визначено вплив авіаційної складової на певних його етапах в умовах впровадження ресурсозберігаючої No-Till технології.

Експериментальними дослідженнями встановлено, що застосування авіаційного транспорту сприяє впровадженню ресурсозберігаючої No-till технології за рахунок мінімізації механічного обробітку посівних площ, що зменшує антропогенне навантаження на грунт.

Розроблена математична модель аналізу використання транспортно-виробничого комплексу при вирощуванні сільськогосподарських культур дозволяє здійснювати раціональний вибір наземних та авіаційних транспортних засобів, залежно від параметрів технологій, видів культур.

Таким чином, є підстави стверджувати про можливість у процесі організації та веденні сільськогосподарського виробництва приймати своєчасні обґрунтовані управлінські рішення з метою отримання максимального прибутку

Ключові слова: технологічний процес, No-till технологія, види ресурсів, технологічна карта, авіаційна техніка, наземна техніка

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1. Introduction

The transport component has a significant impact on agricultural production, depending on its intensity and the level of development of agro-industrial integration, since transport is directly involved in the technological process of growing crops. Efficient use of transport and production resources makes it necessary to introduce modern resource-saving No-till technologies for growing crops, which is impossible without improving the transport component.

Considering that the use of aviation transport in the crop growing process contributes to the introduction of innovative resource-saving No-till technology, the research aimed at further improvement of agricultural works, taking into account the integrated transport system should be considered important [1]. The efficiency of this system lies in the rational use of ground and aviation equipment, resulting in reduced material and financial resources.

2. Literature review and problem statement

Progress in the introduction of resource-saving technologies and efficiency of transport systems in agriculture has contributed to the deepening of the study and improvement of subsurface tillage and sowing machines. The design of a combined diesel subsoiler with additional deformers and paired toothed rollers, which allows improving tillage quality during work on heavy soils is proposed [2]. Based on the calculations [3], it is found that mineral fertilizers reduce the life of the considered elements to a greater extent than organic ones. The studies on sugar beet, soy, sunflower and corn seeds proved the versatility of the proposed sower, the use of which increases the efficiency of sowing seeds of tilled crops and reduces the energy intensity of the process. It is found that one sowing disk allows dosing all the listed types of seeds of tilled crops with sufficient accuracy [4, 5]. However, it should be noted that these works do not specify stages and transport support of the crop growing process. This means that it is not clear how the choice of vehicles for introducing mineral fertilizers and implementing plant protection affects the yield level.

From a practical point of view, this may cause difficulties in determining the efficiency of vehicle use in the agricultural sector. To overcome this problem, studies [6] are conducted that prove that the efficiency of vehicle use is significantly influenced by the following factors: natural climatic conditions, speed, energy indicators, load capacity, transportation distance and many others. It is shown that the most promising direction is to increase the efficiency of process transport support of the agro-industrial complex by optimizing energy consumption. Despite the practical significance of such results, the efficiency of using aviation transport, which is important for the introduction of resource-saving No-till technology, has not been sufficiently considered. Obviously, this is due to the complexity of applying a system approach to solving the problem of minimizing the route of the aircraft while treating the field with the necessary chemicals. This problem is solved in [7, 8] using existing software products that guarantee some alternative choice for users.

The expediency of using aviation transport in comparison with ground equipment when performing agricultural works is confirmed by a yield increase of 10 %, processing speed by 15 times, productivity and fuel consumption by 6 times [9]. However, no relevant mathematical calculations on the use of transport and production resources have been provided to support this hypothesis.

Therefore, there is reason to believe that the lack of certainty on the optimal use of the transport and production complex, taking into account the aviation component, necessitates the need for research in this direction.

In the transport and technological process of ensuring the cultivation of crops, the system of technologies and vehicles should first of all include vehicles with a high level of adaptation to zonal and seasonal variations in operating conditions. This will fully realize the potential qualities laid down in the design and production [6, 10].

The system approach to the study of transport support of the technological process is aimed at identifying functional features, properties, mechanisms of interaction between subsystems and elements, taking into account the influence of the external environment of these systems. Therefore, it is important to determine the place of the transport component in the system of agricultural works (SAW) [11].

The system of agricultural works is a set of methods of performing certain works, which is implemented on a given technical basis, taking into account different types of works. This system should reflect all the factors of the external and internal environment that are significant to achieve the desired effect.

Transport support of the technological process used in the agricultural sector is considered as a necessary element of modern agricultural production, without which a number of important technological operations to ensure the cultivation of crops are impossible. The transport component of crop processing is formed by ground and aviation vehicles, which have their own specific functional characteristics.

Agriculture is rapidly changing due to the introduction of innovative crop growing technologies. There is a high level of expenses for the use of industrial means of reproduction of soil fertility and plant protection from harmful organisms with a high return by yield growth.

Analysis of the impact of agrotechnical measures on the crop yield with their joint implementation showed that about 40 % is accounted for the application of agrochemicals, 15–25 % – for plant protection, 20 % – for varieties and hybrids, and 15–20 % – for soil cultivation, which is the most resource-consuming element of the technology.

With existing technologies of agricultural organization, the yield is 80 % dependent on nature. And with the No-till system, the climate impact on crop efficiency is reduced to 20 %, and the other 80 % depend on the technology and vehicle choice (Fig. 1) [12].

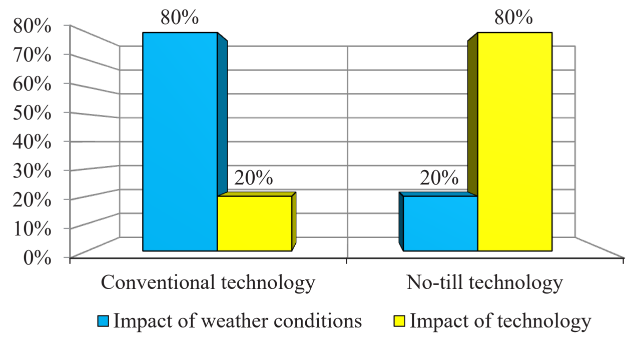

Fig. 1. Level of yield dependence on weather conditions and technology

In the introduction of resource-saving technologies in the agricultural sector, the priority is to preserve and increase material and monetary capital. Minimization of processing reduces the anthropogenic load on the soil, which reduces direct material and technical expenses, labor costs in the technological process and increases the competitiveness of products.

To objectively evaluate the functioning of the transport and technological process to ensure the cultivation of crops, a system approach should be used, since the transport component is a subsystem of the system of agricultural works, as mentioned in previous studies.

The system approach is a concept that emphasizes the importance of complexity, scope and clear organization in research, design and planning. The system approach is based on the well-known dialectical law of interrelation and interdependence of phenomena in the world and society. This approach requires considering the studied phenomena and objects not only as an independent system but also as a subsystem of a large system [13].

Therefore, the transport component for crop growing should be considered in relation to technological processes of agricultural works in the conditions of changing criteria for the efficiency of using ground and aviation vehicles. An important factor of yield level is the choice of vehicles for chemical treatment of agricultural land.

The integrated system of pest, disease and weed protection includes a set of preventive environmentally safe and economically feasible organizational, economic, agricultural, biological, genetic, chemical and other methods.

The average crop production losses from pests are 30 %, and during outbreaks of pests, diseases and heavy weediness of fields can exceed 50 %, and sometimes the crop dies completely. So, without protection measures, even on a high agrotechnical background, it is possible to produce winter wheat grain and even of poor quality only in the range of 20–40 kg/ha, while with proper protection – 70–100 kg/ha.

Therefore, in this case, every third, and sometimes second hectare of arable land, is sown to support the life of harmful organisms.

Therefore, the choice of transport support to ensure the technological process while protecting plants from harmful organisms is extremely important and is achieved through aviation and ground vehicles. Analyzing the structure of ground and aviation vehicles providing the crop growing process, it is proved that the lion's share of treatment of the crop area is performed by ground vehicles. With regard to aviation vehicles, the share ranges from 3 % to 8 %, which indicates insufficient attention to the efficiency of its use. Namely, aviation vehicles can contribute to the introduction of the latest resource-saving No-till technologies [14, 15].

The use of aviation vehicles in agricultural production allows timely and uniform introduction of fertilizers, growth regulators, desiccants and defoliants, protection agents and more. The aviation method of treatment also prevents damage to crops that occurs when using ground equipment. As a result, the increase in crop yield is only up to 30 % on average for cereals and up to 25 % on average for other crops.

3. The aim and objectives of the study

The aim of the study is to optimize the use of transport and production resources for growing crops by the rational use of ground and aviation vehicles taking into account the types of crops and technologies for their cultivation.

To achieve the aim, the following objectives were set:

– to develop a scheme of transport support for the crop growing process, taking into account the aviation component;

– to develop a mathematical model of optimal use of the transport and production complex to ensure the cultivation of crops by the criterion of profit maximization;

– to analyze experimental results of the mathematical model solution.

4. Materials and methods of research on the rational use of transport and production resources

4. 1. Transport support of the crop growing process taking into account the aviation component

The No-till system is the most reasonable approach to crop production, grounded in terms of ecology and economy [13, 16–19]. At the same time, mechanical impact on the soil is excluded, which means that aviation vehicles are more appropriate to use at the stage of plant protection.

There are agro-aviation works on protection of plants against diseases, pests and weeds, desiccation of sunflowers, fertilization of crops with liquid complex and bulk mineral fertilizers during vegetation, foliar feeding of crops, aviation settlement of trichograms. Many years of experience in the use of aviation vehicles have proved that the aviation method is not inferior to the ground method but also exceeds it in terms of biological and economic productivity.

Effective functioning of the transport and technological process to ensure the cultivation of crops is possible only through scientific knowledge about the organization, technology and methods of managing agricultural production. Therefore, it is important to study the technological stages of the crop growing process and involvement of vehicles in the technological operations of each stage. Such research will make it possible to form a scheme of rational transport support of the crop growing process depending on the conditions and requirements of a certain growing stage.

The technology of agricultural works includes the following basic stages of production: preparation for work, provision of work, performance of work and final works [11].

To meet the conditions of resource-saving No-till technologies, it is proposed to involve more aviation vehicles when performing plant protection measures during the growing season, as well as in auxiliary works and sowing.

The block diagram of transport support for agricultural works in growing crops with the distribution of ground and aviation vehicles depending on the type of works is presented in Fig. 2. Such distribution will ensure the rational use of these transport modes, taking into account the technical and economic features.

The transport and technological process in growing crops is a complex object in terms of modeling a single production cycle, which would include all the necessary techniques. One of the tasks to be solved during the preparation for agricultural works is to identify and ensure the readiness of the transport component and technologies to be used, since only the balanced readiness of individual subsystems ensures the timeliness and efficiency of agro-aviation and ground works.

Transport support of crop growing technology includes the following components: agrotechnical methods, sowing, auxiliary work, growing season and harvesting. Ground vehicles (GV) and aviation vehicles (AV) are technical means to achieve the goal, in this case, growing crops and producing high yields (Fig. 2).

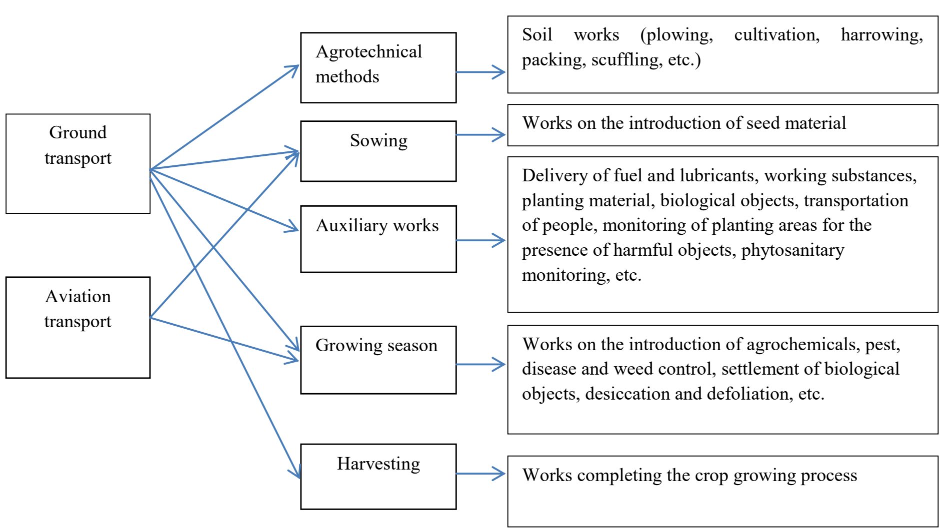

Fig. 2. Diagram of transport support of the crop growing process

Agrotechnical methods include: soil works (plowing, cultivation, harrowing, packing, scuffling, etc.) and are performed exclusively by ground vehicles.

Sowing is performed by specialized agricultural machines. But aircrafts can also do this kind of work, especially when sowing pastures. This type of agro-aviation works is called aerial sowing.

Auxiliary works. These include all auxiliary operations mostly performed by road freight vehicles. These include: delivery of fuel and lubricants, working substances, planting material, biological objects, transportation of people, monitoring of planting areas for the presence of harmful objects, etc. Aviation vehicles can also be involved in auxiliary works in phyto-sanitary monitoring using spectral cameras mounted on aircrafts.

The growing season is the care of crops, which consists of the introduction of agrochemicals, control of pests, diseases and weeds, as well as settlement of biological objects and, if necessary, desiccation and defoliation. These operations can be performed by ground and aviation vehicles. But the advantages of aviation vehicles are obvious and lie in speed, productivity and, as a consequence, a significant increase in crop yields.

Harvesting is carried out exclusively by specialized agricultural machines.

In these circumstances, there has been fierce competition between ground and aviation vehicles. But in order to achieve the common goal of obtaining high and quality yields, it is necessary not to compete with each other, but to choose the rational use of ground and aviation vehicles when performing agricultural works.

4. 2. Mathematical model of optimal use of the transport and production complex for crop growing

For effective functioning of the integrated transport system in the agricultural complex, it is proposed to use an optimization model based on resource allocation and dynamic planning.

From the standpoint of an individual farm, the organization and management of agricultural production can be regarded as managing a complex dynamic system in the face of random factors. The complexity of the system lies in the presence of a large number of different subsystems – land plots, crops, ground vehicles, mechanisms and equipment, aviation vehicles, fertilizers, substances, fuel, people. Dynamism lies in the nature of the production process – growing plants during the natural annual cycle, and in the impact of the previous cycle and previously grown crops and works performed on the effectiveness of actions in subsequent time periods. Random factors are weather conditions, the emergence and spread of pests and diseases, as well as changes in prices for resources, services and finished products.

The farm can grow a certain set of crops K, not all of which are necessarily grown each year. Choosing a subset of crops $K_t \subseteq K$, to grow in the year t is the subject of modeling and searching for optimal options.

As a criterion of optimality, we will consider the profit that the farm can obtain from growing crops by the results of the production year. For each operation $\omega \in \Omega_v$, according to the option $v \in V_{kip}$, expenses $c_{\omega vki}$ (in USD) are defined, which will be considered as variable expenses. Additional resources $\bar{\rho}_\tau^A$, $\bar{\rho}_\tau^H$ of leased equipment should be considered as vectors with discrete increments in element values. That is, it is impossible to rent a half or a quarter of an aircraft. One or two aircrafts can be involved, so the corresponding additional resources may vary discreetly, and a fixed fee must be paid for each change. Therefore, the expenses associated with the use of aviation and ground vehicles involved will have discrete and continuous components.

Let $K_{ipt} \subseteq K$ be a set of crops whose growing is expedient to consider in the field i in the year t after the predecessor p. The choice of crop for the field i in the year t will be determined by the Boolean variables x_{ki}, the sum of which must be equal to one $\sum_{k\in K_{ipt}} x_{ki} = 1$, which means choosing only one crop.

For each crop $k \in K_{ipt}$, there are many options (technologies) of growing V_{kip}. A separate option should be understood not as an abstract technology, but rather a specific process chart linked to the field and its conditions, which include the predecessor crop, soil characteristics, location and terrain. The choice of the option $v \in V_{kip}$ will be determined by the Boolean variables y_{vki}, whose sum for the options $\sum_{v\in V_{kip}} y_{vki} = x_{ki}$ should be zero or one, depending on the value of the variable x_{ki}, which means that at least one growing option of the crop k must be chosen if it is grown on the field i.

Using the above concepts and notation, we write the model as an optimization problem:

$$\sum_{i\in I_t}\sum_{k\in K_{ipt}}\sum_{v\in V_{kip}}\left(d_k U_{vki} - \sum_{\omega\in\Omega_v} c_{\omega vki}\sum_{\tau=\tau_b^\omega}^{\tau_e^\omega} z_{\omega vki}^\tau\right) - \sum_{\tau=\tau_1}^{\tau_N}\left(\left(\Delta\bar{c}_\tau^A, \bar{\rho}_\tau^A\right) + \left(\Delta\bar{c}_\tau^H, \bar{\rho}_\tau^H\right) + \left(\Delta\bar{c}_\tau^L, \bar{\rho}_\tau^L\right)\right) - \left(\Delta\bar{c}^M, \bar{\rho}^M\right) \to \max, \quad (1)$$

where $c_{\omega vki}$ – variable expenses for the operation ω in the growing option v of the crop k on the field i; $i \in I_t$ – index of an individual field; $k \in K_{ipt}$ – index of an individual crop; $v \in V_{kip}$ – index of an individual option; $\omega \in \Omega_v$ – index of an individual operation; $\tau \in [\tau_1, \tau_N]$ – number of an individual period; d_k – expected market value of the crop k; U_{vki} – model variable – expected crop yield k on the field i for the growing option v; $\bar{\rho}^M$ – model variables – vector of additional volumes of fertilizers, substances, fuel purchased for work in the production season; $\bar{\rho}_\tau^A$, $\bar{\rho}_\tau^H$, $\bar{\rho}_\tau^L$ – model variables – volumes of additional aviation and ground resources and employees involved; $z_{\omega vki}^\tau$ – model variable – share of the operation ω of the growing option v of the crop k on the field i performed in the period τ; $\Delta\bar{c}^M$ – vector of the increase in the cost of additional volumes of fertilizers, substances, fuel compared to the cost of stocks included in $c_{\omega vki}$; $\bar{c}_\tau^A$, $\bar{c}_\tau^H$, $\bar{c}_\tau^L$ – vectors of the increase in the cost of additional aviation, ground and human resources compared to the cost included in $c_{\omega vki}$.

To reflect the dependence of the expected crop yield k on the field i for the growing option v on the volumes and terms of operations, we use a linear regression model:

$$U_{vki} = U_{vki}^0 y_{vki} + \sum_{\omega\in\Omega_v}\sum_{\tau=\tau_b^\omega}^{\tau_e^\omega} u_{\omega vki}^\tau z_{\omega vki}^\tau,$$

$$v \in V_{kip}, \quad k \in K_{ipt}, \quad i \in I_t, \quad (2)$$

where y_{vki} is the Boolean variable of the model – the choice of growing option k on the field i; U_{vki}^0, $u_{\omega vki}^\tau$ are regression coefficients reflecting the dependence of the crop yield k on the growing option v on the field i on the volumes and terms of operations $\omega\in\Omega_v$.

This expression reflects the dependence of the expected yield within certain limits. Therefore, it should rather be considered as a dependence of yield deviation on the expected level. We allow incomplete execution not for all operations, and we also limit volume reductions for those we allow. At the same time, this allows taking into account the effect of the terms of operations on the yield using different values of the coefficients $u^{\tau}_{\omega vki}$ for one operation ω: for more favorable periods τ within the interval $[\tau^{\omega}_b,\tau^{\omega}_e]$, this coefficient should be greater, for less favorable – lower. Yield U_{vki} is a variable of the optimization model. These coefficients should take into account the area and features of the field.

Restrictions for volumes of aviation vehicles, ground transport and mechanisms, fertilizers, substances, fuel and other, time of specialists and workers involved in the period τ that can be used by the farm during the period are determined by the expressions:

$$\sum_{i\in I_t}\sum_{k\in K_{ipt}}\sum_{v\in V_{kip}}\sum_{\omega\in\Omega_v}\bar{w}^{A}_{\omega vki}z^{\tau}_{\omega vki}\le\bar{\rho}^{A}_{\tau},\quad \tau\in[\tau_1,\tau_N]; \tag{3}$$

$$\sum_{i\in I_t}\sum_{k\in K_{ipt}}\sum_{v\in V_{kip}}\sum_{\omega\in\Omega_v}\bar{w}^{H}_{\omega vki}z^{\tau}_{\omega vki}\le\bar{R}^{H}_{\tau}+\bar{\rho}^{H}_{\tau},\quad \tau\in[\tau_1,\tau_N]; \tag{4}$$

$$\sum_{\tau=\tau_1}^{\tau_N}\sum_{i\in I_t}\sum_{k\in K_{ipt}}\sum_{v\in V_{kip}}\sum_{\omega\in\Omega_v}\bar{w}^{M}_{\omega vki}z^{\tau}_{\omega vki}\le\bar{R}^{M}+\bar{\rho}^{M}; \tag{5}$$

$$\sum_{i\in I_t}\sum_{k\in K_{ipt}}\sum_{v\in V_{kip}}\sum_{\omega\in\Omega_v}\bar{w}^{L}_{\omega vki}z^{\tau}_{\omega vki}\le\bar{R}^{L}_{\tau}+\bar{\rho}^{L}_{\tau},\quad \tau\in[\tau_1,\tau_N], \tag{6}$$

where $\bar{w}^{A}_{\omega vki}$, $\bar{w}^{H}_{\omega vki}$, $\bar{w}^{M}_{\omega vki}$, $\bar{w}^{L}_{\omega vki}$ are the vectors of direct expenditures of aviation and ground resources, fertilizers, substances, fuel and manpower for the operation ω in the growing option v of the crop k on the field i; $\bar{R}^{H}_{\tau}$, $\bar{R}^{M}$, $\bar{R}^{L}_{\tau}$ are the vectors of ground resources, fertilizers, substances, fuel and human resources available on the farm. The availability of ground and human resources is limited for each period; fertilizers, substances, fuel – for all periods.

Allowable limits of variations in the volume of operations, depending on whether the growing option is chosen or not ($0\le\alpha_{\omega vki}\le 1$) are described by the expression:

$$\alpha_{\omega vki}y_{vki}\le\sum\nolimits_{\tau\in[\tau^{\omega}_b,\tau^{\omega}_e]}z^{\tau}_{\omega vki}\le y_{vki},$$

$$\omega\in\Omega_v,\quad v\in V_{kip},\quad k\in K_{ipt},\quad i\in I_t, \tag{7}$$

where $\alpha_{\omega vki}$ is the coefficient of permissible reduction of the volume of operations performed $\omega\in\Omega$ in the growing option v of the crop k on the field i, for which the adequacy of the formula (1) of yield dependence on the volumes and terms of operations is preserved; $\left[\tau^{\omega}_b,\tau^{\omega}_e\right]$ is the interval of periods during which the operation can be performed, including the earliest and most recent execution.

The logical condition of whether the growing options will be chosen depending on whether the crop is grown on the field has the following form:

$$\sum\nolimits_{v\in V_{kip}}y_{vki}=x_{ki},\quad k\in K_{ipt},\quad i\in I_t, \tag{8}$$

where x_{ki} is the Boolean variable of the model – the choice of crop to be grown on the field i.

The requirement to choose one crop to grow on the field in the year is described by the expression:

$$\sum\nolimits_{k\in K_{ipt}}x_{ki}=1,\quad i\in I_t. \tag{9}$$

The scope of the variables x_{ki}, y_{vki}, $z^{\tau}_{\omega vki}$ is defined by the following expressions:

$$x_{ki}\in\{0,1\},\quad k\in K_{ipt},\quad i\in I_t; \tag{10}$$

$$y_{vki}\in\{0,1\},\quad v\in V_{kip},\quad k\in K_{ipt},\quad i\in I_t; \tag{11}$$

$$z^{\tau}_{\omega vki}\ge 0,\quad \tau\in[\tau_1,\tau_N],\quad \omega\in\Omega_v,$$

$$v\in V_{kip},\quad k\in K_{ipt},\quad i\in I_t. \tag{12}$$

The scope of the variables $\bar{\rho}^{A}_{\tau}$, $\bar{\rho}^{H}_{\tau}$ is calculated by the expression:

$$\bar{\rho}^{A}_{\tau}\in\bar{\Theta}^{A},\quad \bar{\rho}^{H}_{\tau}\in\bar{\Theta}^{H}, \tag{13}$$

where $\bar{\Theta}^{A}$, $\bar{\Theta}^{H}$ are sets that are the scope of the variables $\bar{\rho}^{A}_{\tau}$, $\bar{\rho}^{H}_{\tau}$ that can be either continuous or discrete.

These variables are considered as discrete, which can take on a finite set of values, and reflect the ability of the farm to involve third-party aviation and ground resources. But for some types of resources, continuous variables are also possible.

5. Analysis of experimental results of mathematical model solution

The proposed model allows making a rational choice of transport and production resources, crops, area for these crops and technologies of their growing. Calculation using the model determines the optimal use of own and additional resources by the criterion of profit maximization. By solving the problem (1)–(13) with different values of fixed parameters, which define the list of crops, fields, technologies, resources, we can investigate the effect of changes in these parameters on the optimal solution and profit.

To demonstrate this possibility, an example of the data of the Ukrainian enterprise «Yana Plus» was chosen, which contained: 4 crops, 10 growing technologies [20]. The variables of the model x_{ki} were fixed, the variables y_{vki} were considered as continuous, inequalities were used in the constraints (12). The problem was solved as a standard linear programming problem.

Among the technologies considered were both traditional and No-till technologies that use and do not use aviation vehicles.

The entire planning interval consisted of two calendar years, which allowed taking into account all operations of growing both winter and spring crops. Individual periods τ were calendar days. Approximately 450 periods (days) were used in the planning interval. Specifically, the number of periods considered in a particular problem depended on the crops and technologies chosen for the problem. The first period was January 1 of the first year. The number of the minimum period used in optimization problems was 180th and the maximum – 630th.

In the example provided, a field was allocated for each crop and the possibility of growing other crops in that field was not considered. But the possibility of reducing the area of crop growing in the field, as well as the possibility of using different crop growing technologies in different parts of the field, was considered.

The technologies of growing different crops of the enterprise are considered, given in Table 1.

Table 1

Effect of growing technology on yield and cost of 1 ha, taking into account the transport component

No.	Crop	Yield, t/ha	Expenses, USD/ha	Growing technology	Use of aviation vehicles
1	Sunflower	2.3	376.96	Process chart of sunflower growing	No
2	Sunflower	2.0	242.19	No-till Process chart of sunflower growing	Yes
3	Corn for grain	5.2	469.09	Process chart of growing corn for grain	No
4	Corn for grain	4.5	336.0	No-till Process chart of growing corn for grain	Yes
5	Blue lupine	2.2	350.27	Process chart of growing blue lupine	Yes
6	Blue lupine	2.2	333.5	No-till Process chart of growing blue lupine	Yes
7	Winter wheat	5.0	238.25	Technology of growing winter wheat after non-fallow predecessors	Yes
8	Winter wheat	5.0	231.63	Technology of growing winter wheat after non-fallow predecessors (2)	Yes
9	Winter wheat	4.9	210.72	No-till technology of growing winter wheat after non-fallow predecessors (1)	No
10	Winter wheat	4.9	194.77	No-till technology of growing winter wheat after non-fallow predecessors (2)	Yes

The «Yield» column indicates the maximum yield that can be achieved by performing all technological operations in full. The «Expenses» column indicates the expenses corresponding to this yield.

The use of aviation vehicles was considered in the following operations: for wheat – aerial treatment with urea in May, yield losses in case of non-performance 10–25 %; for corn – herbicide application in July, losses up to 30 %; for sunflower – aerial application of agrochemicals in spring and desiccation in autumn, losses for each operation up to 30 %; for lupine – aerial application of agrochemicals in spring, yield losses in case of non-performance up to 20 %.

Table 2 lists the types of resources considered in the example and their number per day, which made it possible to perform all technological operations in full for optimally selected technologies. These amounts of resources were thought to be available every day throughout the planning interval.

Table 2

Use of transport and production resources per day

Resource	Maximum available volume per day	Units
Tractor drivers, drivers	220	man-hours
Workers	70	man-hours
Alpha_Hardi	10	hours
Case 340	30	hours
Claas	45	hours
CLAAS_Xerion	10	hours
Manitou	20	hours
An-2	20	hours
GAZ	25	hours
GAZEL	16	hours
GAZ-SAZ-3502	400	t·km
DON-1500	52	hours
DT-75	30	hours
ZAV-60	35	hours
K-744	40	hours
KAMAZ	125	hours
KAMAZ	4,000	t·km
MTZ-1221	5	hours
MTZ-80/82	30	hours
SK-5	1	hours
T-150	20	hours
HTZ-17221	15	hours

Among the listed resources are the names of tractors, combines and machines. The An-2 aircraft is considered as aviation vehicle. For most resources, the maximum daily usage is specified in hours, for two cars – in ton-kilometers. This is due to the process charts used.

A number of general parameters were used in the calculations (Table 3).

Table 3

Cost indicators of resource usage

Parameter	Value	Unit
Cost of 1 t·km of transportation	0.06	USD
Cost of 1 kWh of electricity	0.07	USD
Diesel price	0.78	USD/l
Gasoline and oil increase ratio	1.1	–
Payroll charges	0.261	–
Depreciation costs	90 %	–

With the specified parameter values and with complete provision of resources for all crops, No-till technologies are used in all (100 %) of the planned areas and the planned yield is reached, which is the maximum in the given model. The economic result is shown in Table 4.

We will call this result «basic» and compare with it the results of calculations at a different ratio of resources.

The research with the «prohibition» to use aviation vehicles, that is, in the absence of aviation resource is conducted (Table 5).

Table 4

Results of the calculations for the specified parameter values and full provision of resources using the No-till technology

Crop	Area used, ha	Yield, t/ha	Income, thousand USD	Expenses, thousand USD	Growing technology from Table 1
Sunflower	1,391 (100 %)	2.0 (100 %)	1031.0	337.0	2
Corn for grain	431 (100 %)	4.5 (100 %)	324.0	145.0	4
Blue lupine	18 (100 %)	2.2 (100 %)	8.0	6.0	6
Winter wheat	678 (100 %)	4.9 (100 %)	616.0	132.0	10
Total	2518	–	1977.0	620.0	–
Profit	–	–	1357.0	–	–

Table 5

Yield level in the absence of the use of aviation vehicles in certain technological operations

Crop	Area used, ha	Yield, t/ha	Income, thousand USD	Expenses, thousand USD	Growing technology from Table 1
Sunflower	1,391 (100 %)	1.98 (86 %)	1021.9	496.1	1
Corn for grain	431 (100 %)	5.2 (100 %)	373.6	202.2	3
Blue lupine	18 (100 %)	1.72 (80 %)	5.9	5.4	6
Winter wheat	678 (100 %)	4.9 (100 %)	615.3	142.9	9
Total	2,518	–	2016.7	846.5	–
Profit	–	–	1170.1	–	–

With such constraints, technologies 1, 3, 9, which do not have aviation operations, are used in the optimal solution of the problem. At the same time, technologies 1 and 3 are not No-till, and technologies 6 and 9 are No-till technologies. All areas are involved. For blue lupine, the yield is reduced due to losses from non-performance of aerial application of agrochemicals. Sunflower yield losses are due to the lack of workers and the inability to perform all works for all crops in some periods. Increasing the workers' resource to 250 man-hours a day is enough to get a 100 % sunflower yield using «conventional» technology. At the same time, its yield is higher – 2.3 t/ha compared to 2.0 for No-till technology. But with all the resources available, the optimal solution is No-till technology with lower yields, but lower expenses.

The «reaction» of the optimal problem solution to changes in the amount of available resources is not as «trivial» as it might seem. Thus, it is shown above that additional man-hours are needed to achieve 100 % implementation of technology 1.

But it turns out that technology 1 is also performed when reducing the available amount of man-hours of workers with a sufficient amount of flight hours. Namely, when reducing the resource of workers in the basic option to 40 man-hours a day, we get such an optimal solution (Table 6).

In this solution, the area for winter wheat is reduced, the volume of corn operations is reduced, and the area allocated for sunflower is divided into two parts where different technologies are used. This provides the most efficient use of workers' scarce resources. All other resources in this option are not scarce.

Table 6

Yield level when reducing the resource of workers to 40 man-hours a day

Crop	Area used, ha	Yield, t/ha	Income, thousand USD	Expenses, thousand USD	Growing technology from Table 1
Sunflower	172 (12 %)	2.3 (100 %)	146.9	65.0	1
Sunflower	1,219 (88 %)	2.0 (100 %)	902.7	295.2	2
Corn for grain	431 (100 %)	3.8 (84 %)	271.2	140.9	4
Blue lupine	18 (100 %)	2.2 (100 %)	7.4	6.0	6
Winter wheat	542 (80 %)	4.9 (100 %)	492.1	105.7	10
Total	2,382	–	1820.3	612.7	–
Profit	–	–	1207.6	–	–

Studies are conducted on the response of the optimal problem solution to reducing the time of using tractors, combines and machines. In the following calculation, this resource was reduced to 50 % for Case 340, GAZ-SAZ-3502, DON-1,500, KAMAZ. The man-hours and flight resources remained at the basic calculation level (Table 7).

Table 7

Yield level when reducing the time of using tractors, combines and machines

Crop	Area used, ha	Yield, t/ha	Income, thousand USD	Expenses, thousand USD	Growing technology from Table 1
Sunflower	1,391 (100 %)	2.0 (100 %)	1030.4	336.9	2
Corn for grain	416 (96 %)	4.5 (100 %)	312.3	139.9	4
Blue lupine	18 (100 %)	2.2 (100 %)	7.4	6.0	6
Winter wheat	150 (22 %)	4.9 (100 %)	136.6	31.7	9
Winter wheat	222 (33 %)	4.9 (100 %)	201.8	43.3	10
Total	2047	–	1688.2	557.8	–
Profit	–	–	1130.4	–	–

The results of the studies show that in this case all No-till technologies presented in the problem are used, the maximum crop yield is preserved, but the area for crops is reduced. This indicates that No-till technologies are the least resource-intensive in terms of using ground vehicles.

Calculations involve the collection, analysis and primary processing of data, storage of data by certain means in appropriate forms, preparation of data for calculations, analysis and storage of results.

Primary processing and storage of the data were done using Excel. Individual Excel pages corresponded to the data divided into groups. These were general data, data on crops, data on crop growing technologies, data on resources and data on process charts of growing individual crops by individual technologies.

To prepare data for the optimization problem in the optimization program format and to process the optimization results, the Visual Basic for Application programming language was used, which allows creating menus and processing data from Excel worksheets.

For optimization, the American Optimal Decisions (AOrDa) Portfolio Safe guard (PSG) optimization package was used [21].

The view of the worksheet with general parameters is given above (Table 3). The worksheet for selecting crops, growing areas and selling prices is as follows (Table 8).

The user (the person making the calculations) can select the crops to be considered for the optimization problem, their maximum area and estimated selling price. The name and code of the crop are selected from the worksheets of the process charts. The crop code is used to formulate the optimization problem.

Table 8

Example of selecting crops, growing areas and selling prices

Crop	Crop code	Select for optimization (1/0)	Area, ha	Selling price, USD/t
Sunflower	C	1	1.391	370.4
Corn for grain	KZ	1	431	16.7
Blue lupine	L	0	18	185.2
Winter wheat	PO	1	678	185.2

The user can select the technologies that will be considered in the optimization problem and set the yields different from those indicated in the process charts. Planned expenses are reference information. The technology code is the same as the technology worksheet and was used to form the optimization problem.

The optimization problem is formed by creating matrices for the linear programming problem in the PSG format. The condition of the linear problem in the PSG format corresponds to the model (1)–(13). It remains unchanged when data are changed and is shown in Fig. 3. The objective function of the problem corresponds to (1). The first constraint is (2). The second constraint is the constraint system (3)–(6). Constraints three, four – (7), (8).

```
maximize
 linear(pmatrix_objective)
constraint_1: calculate_crop, = 0
 linearmulti(pmatrix_urozay)
constraint_2: resources_in_time, <=
 vector_resource_limit_in_time
 linearmulti(pmatrix_in_time)
constraint_3: sum_z_y, <= 0
 linearmulti(pmatrix_zy)
constraint_4: sum_y, <= 1
 linearmulti(pmatrix_y)
constraint_5: sum_of_expenditures, = 0
 linearmulti(pmatrix_sum_time)
Box: >= lower_bounds_z
Solver: car
```

Fig. 3. Recording the problem (1)—(13) in the PSG format

The detailed result of the solution is formed by the vector of optimal values of the problem variables and by the input data of the problem.

The results of optimal values for crops are presented in Table 9.

Table 9

Results of optimal values for crops

Crop	Crop code	Selected for optimization (1/0)	Area set, ha	Area used, ha	% used
Sunflower	C	1	1,391	1391.0	100.0 %
Corn for grain	KZ	1	431	273.5	63.5 %
Blue lupine	L	1	18	18.0	100.0 %
Winter wheat	PO	1	678	352.5	52.0 %

In addition, expenses for individual items are shown in Table 10.

Table 10

Cost indicators of resource usage

Item	Expenses	Units
Depreciation expenses	5549.2	USD
Plant protection expenses	66191.6	USD
Agrochemicals expenses	166425.0	USD
Electricity expenses	4858.4	kV·h
Wage fund expenses	13452.2	USD
Other expenses	82597.1	USD
Seed expenses	117572.5	USD
Fuel expenses	58308.2	liters
Total mileage	25378.4	t·km

Resource usage is shown in Table 11. As stated in Table 2, the amount of resources per day is measured in hours (suffix _H) or t*km (suffix _T). Personnel resource is measured in man-hours.

The maximum resource usage per day is found in the analysis of the result of solving the optimization problem, namely, the obtained values of direct variables. If the maximum usage equals the maximum available volume per day, this does not mean that the resource is «scarce». Rather, it is a property of solving the linear programming problem when resource usage is uneven over periods when it could be used in a particular operation. One of the periods of the maximum resource usage is shown in Table 11. Resource scarcity is determined in the analysis of the obtained values of dual variables. Their values indicate how much profit can be increased by increasing the available resource volume by one. This is a conditional value because as one type of resource increases, another resource may become «scarce» and there will be no expected profit increase. Usage amount is the amount of resource usage over all periods of the planning interval.

Table 11

Selection of transport and production resources for the crop growing process

Resource	Maximum available volume a day	Maximum received usage a day	Period with maximum usage	Resources that the program deems scarce and effect of increasing the available volume by 1 (thousand USD)	Usage amount for all periods
EmPtY_H	40	40.0	257	0	293.7
EmPtY_T	0	0	0	0	0
Case_340_H	20	20.0	485	23.7	204.5
HTZ-17221_H	15	10.0	565	0	144.7
K-744_H	40	0	195	0	0
Manitou_H	20	16.7	485	0	126.3
An-2_H	20	20.0	443	0	464.8
GAZ_H	25	25.0	485	0	280.6
GASEL_H	16	16.0	489	0	146.1
GAS-SAZ-3502_T	200	200.0	226	0	5992.1
DON-1500_H	26	26.0	546	9.7	264.3
DT-75_H	30	30.0	433	0	49.9
ZAV-60_H	35	35.0	546	0	71.4
CLAAS_Xerion_H	10	0	243	0	0
KAMAZ_H	125	125.0	623	0	3858.5
Robit	70	70.0	468	0	1705.4
MTZ-1221_H	5	5.0	485	0	20.5
MTZ-80/82_H	30	29.1	433	0	258.1
SK-5_H	1	1.0	530	0	2.7
T-150_H	20	17.9	258	0	62.9
Vodii	220	218.2	487	0	5112.6
Alpha_Hardi_H	10	10.0	565	0	144.7
Claas_H	45	45.0	617	0	471.1

6. Discussion of the results of the study of mathematical modeling of the transport and production complex taking into account the aviation component

When developing the scheme of transport support for the crop growing process (Fig. 2), to meet the conditions of resource-saving No-till technologies, it is proposed to involve more aviation vehicles when performing plant protection measures during the growing season, as well as during auxiliary works and sowing. Such distribution ensures the rational use of aviation and ground transport, taking into account technical and economic features. Sowing is performed by specialized agricultural machines. But aircrafts can also do this kind of work, especially when sowing pastures.

As for auxiliary works, aviation vehicles may also engage in phyto-sanitary monitoring works by means of spectral cameras mounted on aircrafts.

The growing season is the care of crops, which consists of the introduction of agrochemicals, control of pests, diseases and weeds, as well as settlement of biological objects, desiccation and defoliation. These operations can be performed by ground and aviation vehicles. But the advantage of aviation vehicles is obvious and lies in speed, productivity and, as a consequence, a significant increase in crop yields, which is proved in [9].

Using the developed mathematical model (1)–(13), studt ies were carried out on the possible solution of various problems at different values of fixed and variable parameters, which made it possible to study the effect of changes in these parameters on the optimal solution and profit.

The results of the calculations show that if all resources are sufficient, the optimal solution is No-till technology with lower yield but lower expenses. According to this result (Table 4), the income amounted to 1977.0 thousand USD, expenses 620.0 thousand USD and profit 1357.0 thousand USD. This result (Table 4) was compared with the results of calculations at a different ratio of resources:

– non-performance of some technological operations by aircraft vehicles (Table 5) – the income amounted to 2016.7 thousand USD, expenses 846.5 thousand USD and profit 1.170,1 thousand USD;

– reduction of the available man-hours of workers with sufficient flight hours (Table 6) – the income amounted to 1820.3 thousand USD, expenses 612.7 thousand USD and profit 1207.6 thousand USD;

– reduction of the time of using tractors, combines and machines (Table 7) – the income amounted to 1688.2 thousand USD, expenses 557.8 thousand USD and profit 1.130,4 thousand USD.

It is determined that No-till technology is the least resource-intensive in terms of using ground vehicles.

Such conclusions can be considered appropriate from a practical point of view, since they allow reasonable management of transport and production resources and making timely informed management decisions for maximum profit. However, it should be noted that the use of aviation transport is costly, so it is necessary to look for ways to reduce expenses.

To further improve the developed mathematical model, it is necessary to consider the differentiated application of the No-till system depending on the soil and climatic conditions of the region, availability of appropriate facilities of the farm and material and technical base.

Further research can be developed to take into account risks, the management of which involves the choice between alternatives that have uncertain results. The most common sources of risk in crop production are as follows:

– insufficient precipitation or drought can lead to low crop yields;

– hail or heavy rain can damage or destroy crops;

– production risk is the failure of technical equipment during the production season, which leads to the impossibility of timely harvesting.

7. Conclusions

1. On the basis of the conducted research, the block diagram of transport support of agricultural works during growing crops with the distribution of ground and aviation vehicles, depending on the type of works was developed. Such distribution will ensure the rational use of these transport modes, taking into account the technical and economic features.

2. The developed mathematical model for optimal use of the transport and production complex allows making timely reasonable management decisions in the process of organization and management of agricultural production in order to maximize profits.

3. Using the developed mathematical model, studies were carried out on the possible solution of various problems at different values of fixed and variable parameters, which made it possible to investigate the effect of changes in these parameters on the optimal solution and profit. The «basic» option was identified, consisting of full provision of resources for all crops using No-till technology in all (100 %) of the planned areas, and the planned yield was reached, which is the maximum in this model. Under this option, the income amounted to 1977.0 thousand USD, expenses 620.0 thousand USD and profit 1357.0 thousand USD. The results obtained were compared with the results of calculations at different ratios of resources. The results of the comparison indicate that No-till technologies are the least resource-intensive in terms of using ground vehicles.

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