Efficiency and unity of planting and harvesting complexes in the grain subcomplex

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Abstract. The article uses a systematic approach when considering the implementation of field work by planting and harvesting complexes. It was established that for the full use of the capabilities of these complexes at minimal cost, mechanized work must be carried out at the maximum values of the shift time utilization factors. The tabular form shows the values of the shift time utilization factors for the conditions of the Non-Chernozem Zone of Russia. The choice of work strategy determines the maturation rate, weather conditions, and the availability of technical equipment. Numerical compositions of planting and harvesting complexes per 1 ha are proposed, which are presented in tabular form when aggregated with tractors of class 1.4; 2; 3. Effectiveness evaluation of the complex functioning should be based on the activities of all subsystems to implement the work plan. Such an evaluation of the daily work of the complex can serve as a coefficient of work intensity equal to the ratio of the amounts of actually completed work to the planned ones. The conclusions establish ways to improve mechanized processes for planting and harvesting grain crops, and as an optimal option, the option of maximizing the use of shift time due to the introduction of new organizational and technical forms was chosen. As a result, a mathematical model for the functioning of planting and harvesting complexes in the production of grain crops for the Non-Chernozem Zone of Russia, which can also be used for other regions, was developed.

1. Introduction
In modern conditions, much attention is paid to the development of the agricultural complex of Russia and foreign countries in order to increase the level of food security in the framework of existing sanctions and the food embargo. In this regard, scientists from different countries are looking for approaches, methods and tools to improve the crop and livestock sectors of agriculture to increase the food supply of our states [1-17].

To make managerial decisions in the system of applying planting and harvesting complexes, in practice, both informal and formalized methods are used. With informal methods, (manager) a specialist makes decisions based on his own considerations according to past experience and intuition, without any reasoning. Whereas formalized decisions are carried out according to clear rules, procedures and recommendations. The adoption of such a class of decisions is based on two groups of methods: logical modeling and optimizations founded with the use of mathematical models.
In logical modeling, they use the so-called rules (principles), which are developed by highly qualified specialists, for applying by their users, who will make decisions. The rules establish what needs to be done and in what situations. Thanks to these rules, simple performers of lower qualification have a competent hint when making decisions.

The implementation of optimal solutions using software has two significant advantages: it provides a quick answer to the problem being solved and provides the possibility of conducting extensive experimentation, the implementation of which on a real object in an economic environment is simply not possible.

However, with regard to mathematical models for determining the optimal composition, structure and use of technical means for mechanizing the processes of planting and harvesting crops, they should be developed taking into account the specific features of cultivation technologies.

The mathematical models existing in this area of research can be divided into two varieties conditionally: analytical and statistical.

When constructing the first type of models, the main quantitative indicators of the processes (machine complexes, technological operations, etc.) should be connected by analytical dependencies. When designing statistical models (which include simulation models, the Monte Carlo model), it is necessary to take into account the presence of an element of randomness in production activities, that these are not deterministic models and therefore must obey the laws of distribution of random variables (and this is what allows statistical models to be studied).

The statistical model becomes adequate to reality due to the possibility of taking into account non-linearity, dynamism, the probability of occurrence of natural and other phenomena. The implementation of such a model makes it possible to carry out the so-called "field experiment" on an accelerated time scale. Statistical models presented as one-dimensional and multi-dimensional regression equations find application in optimizing the parameters of a machine-tractor fleet. However, the classical regression analysis is carried out without taking into account the features of the technological process, which leads to model errors, to their instability, which indicates their unreliability and the impossibility of their implementation.

Therefore, they often use the Gauss formula for solving such problems, referred to in the literature as the least squares method, since it is based on minimizing the sum of squares of the difference between the experimentally obtained values of the function from the calculated ones:

\[
\sum_{j=1}^{n} \left( y_j - \tilde{y}_j \right)^2 \rightarrow \min,
\]

where: \( y_j \) - experimentally obtained values;
\( \tilde{y}_j \) - calculated values based on the regression equation (1).

Because of their simplicity and versatility, optimization models based on linear programming methods are widely used. The simplex method (the method of successive improvement of the plan) is considered the main one when solving linear programming problems. To solve certain linear programming problems, they use the potential method and the differential rent method.

It should be noted such mathematical models, which are based on dynamic programming. It is advisable to implement these models if the given variables are studied in motion (dynamics), and their values are determined over time depending on the change in the value of the objective function.

The main mathematical dependence for the above models is differential equations of the form:

\[
X = F(A, x, y, t),
\]

where \( X \) - vector of derivatives of the first order;
\( x, y, t \) - vectors of the arguments of the system equations;
\( A \) - unknown model coefficients. Partial differential equations, as a rule, are reduced to the form (2) by various methods.
For the development of technological processes of planting and harvesting complexes based on dynamic programming, various heuristic approaches are used. However, the least universal method is still the least squares method.

To select a method, it is necessary to analyze their capabilities in identifying the performance of work on a reference model. So, when optimizing the processes of planting and harvesting grain in specific economic conditions using the identification method of integrating the differential equation with the expansion of input-output disturbances in a Fourier series, it is possible to achieve as close as possible to real values, but still its error is greater than when applying nonlinear methods programming.

In the technology of grain production at all stages (levels), much attention is paid to the selection of optimal options, from route maps to the choice of technological lines, from optimization of technical means to conditions and to selection of conditions for technical means, from conditions for technical means to optimization of technological processes, etc. that allow to manage the production process.

At each design level, a multivariate procedure is formed, as a result of which it is possible to form a tree of goals and admissible (within the specified technical limitations) process options (Fig. 1).

The vertices of the tree - C correspond to the operation of developing design solutions, and the arcs R correspond to the selected variants of these solutions. The arcs of the lowest level tree characterize the selected options for a given degree of detail. In general, the process of multi-level design is presented in the form of successive transformations of various levels until the selection of the optimal option at the lower level according to a given criterion.

The advantages of the target model that considers the multi-level process of technological design include the fact that it enables the user at each level to select several options for solutions that are closest to the optimal one according to indicators of interest. At the final stage of design, based on the qualifications and competence of the user, one of the most effective technology options is selected that meets the quality criterion.

For a comparative assessment of cultivation technologies, Pareto optimization methods can also be used. The essence of the method is that it allows to analyze several proposed options for solving the same
The choice of effective technology among those considered is based on decision-making methods. Among them, theoretical methods of single-criterion and multicriteria analysis can be singled out. Using which comparison of optimization criteria is made between any two solution options. Priority is given to that technology option in which the optimization criterion exceeds the performance of another option. The advantages of Pareto optimization are that, as a result, comparisons are ranked by technology efficiency. At the last iteration, the best option is determined.

The analysis of the applied models and methods of their implementation for the selection of effective solutions in agricultural production showed their diversity and at the same time, many factors that need to be taken into account in specific business conditions influence the execution of the technological process. Some of which we propose to take into account in the future.

Observance of agrotechnical terms of work with their proper quality is the main condition for minimizing crop losses. The duration of harvesting - $T_{hav}$, basically determines the period of maturation of grain - $T_{mat}$. In turn, $T_{mat}$ depends on the duration of sowing (planting) - $T_s$, soil, climatic and meteorological conditions. Consequently, the structures and the numerical compositions of sowing (SC) and harvesting and transport complexes (HTC) should be closely related with each other. Therefore, a systematic approach is needed when considering the management (design, planning and operation) of SC and HTC. Design of SC and HTC farms consists of successive stages: technological and technical.

At the technological stage, for a given volume $S$ (ha) of work for a particular farm, the following is calculated: duration of $T_s$, $T_{mat}$, $T_1$ - mowing duration, $T_2$ - threshing duration, $T_3$ - duration of direct combining; share $\gamma$ of separate harvesting, $\delta_k$ losses on the $k$-th day of harvesting, etc., i.e. formulate the technological task for the complexes.

On the technological stage, the structure and composition of the SC and HTC is calculated so that with the chosen $J$ - strategy of work and their durations corresponded to this task.

The initial information for the technical design of the complexes should contain: the technological task, the strategy $J$ of works, the average standard productivity $W_j$ (ha/h) of the machines of the complex for each type of work per day ($j=1,v$), as well as the parameters of the service subsystems, i.e. the average calendar time $T_{р}^i$ for the failure of one machine at the $j$-th job in the $i$-th subsystem and the average duration $T_{в}^i$ of one machine maintenance in the same subsystem ($i=1, F_j$) i.e.

$$L(S, \gamma, J, t_j, t_j, \omega_j, T_j, T_{pji}, T_{nji}, f = 1v; \ i=1,F_j), \quad (3)$$

To make full use of the capabilities of the complexes at the lowest material and labor costs, its technical design should be carried out at the maximum values of the shift time utilization factors $K_{j\max}$ i.e.

$$K_{j\max} = \left(\sum_{i=1}^{F_j} P_j + 1\right)^{-1}, \quad (4)$$

where $F_j$ is the number of service subsystems of machines and their operators outside their working hours, $P_j = T_{nji}^i \cdot T_{в}^i$ are the parameters of the service subsystem.

The values of $K_{j\max}$ for the conditions of the Non-Chernozem zone of the Russian Federation according to our observations are presented in Table 1.

| Days       | Planting complexes for | Harvesting and transport complexes for |
|------------|-----------------------|----------------------------------------|
|            | Cultivation j=1      | Sowing j=2                             |
| Work       | 0.85                  | 0.68                                   |
| Calendar   | 0.0                   | 0.58                                   |
|            | Mowing j=1            | Thresholding and direct combining j=2,3 |
| Work       | 0.85                  | 0.72                                   |
| Calendar   | 0.70                  | 0.55                                   |
When performing work in line technology, the minimum shares of the complex’s machines engaged in previous and subsequent works:

\[
\alpha_{\text{min}} = (1 + \frac{\omega_t k_1}{\omega_t + \omega_s k_{j+1}})^{-1},
\]

\[
\beta_{j+1\text{min}} = 1 - \alpha_{\text{min}},
\]

In the general case, for HTC \( \alpha \) and \( \beta \) are the shares of reaping machines and suitable threshers from the total number \( N \) of combines; for SC \( \alpha \) and \( \beta \) - the shares of cultivators and seeding planters of the total number \( M \) of machine-tractor aggregates (MTA).

Depending on the \( T_{\text{mav}} \) of meteorological conditions, HTC can function according to three strategies.

The first strategy – before the possible start of threshing rolls (\( t_2^9 = T_n = 3-6 \) days), when the stage of grain maturation is not yet completed, the optimal period for mowing is established. Then, when the stage of grain maturation is completed, the stage of direct combining is started. The second strategy is based on the first strategy, and the third strategy is the same as strategy 1, but with the ability to choose the optimal period for mowing. The choice of work strategy is determined by the rate of crop maturation, weather conditions, the availability of equipment, personnel and facilities. However, the selected technology should not violate the technological task. For each strategy, algorithms for calculating the work plan have been developed. These algorithms are easily implemented on a PC. The Ipatov method of harvesting provides for consistent mowing and threshing (strategy 3). However, due to the good organization of work and a sufficient amount of equipment in the HT, we get a shorter duration of harvesting than the optimal service time for all types of complexes i.e. \( T_{\text{hav}} = T_n + T_2 \).

Concerning PC management - a special case of HTC at \( \gamma = 1 \). To maintain moisture in the soil, its work is organized by strategy 2 (\( t_2^9 \leq 1 \)).

The number of days the complex operates per 1 ha is

\[
x\gamma = \frac{\gamma}{\omega_1 t_1 k_1 + \omega_2 t_2 k_2 + (1 - \gamma) / \omega_2 t_2 k_2}.
\]

Then, for mowing during \( T_1 \) and threshing grain during \( T_2 \) days by strategy 1, a sufficient number of combines in the HTC is

\[
N^1 = x(\gamma) \times S \times \left[ T_2 + \alpha t_1^9 + (1 - \beta) \times (T_1 - t_2^9) \right]^{-1},
\]

When applying the strategy 2 (\( \alpha = \alpha_{\text{min}} \); \( \beta \geq \beta_{\text{min}} \), and strategy 3 (\( \alpha = \alpha_{\text{min}} T_c \)), the numerical composition of the PC according to (5) at \( \gamma = 1 \) is

\[
M = x \cdot S(\beta_{\text{min}} \cdot T_s + \alpha_{\text{min}} T_c)^{-1},
\]

where \( T_c \) and \( T_s \) are the duration of cultivation and sowing of grain.

With the correct organization of work \( T_c = T_s \) for each climate zone, statistical dependencies between \( T_{1,2} \) and \( T_s \) can be determined:

\[
T_{1,2} = \alpha_{1,2} T_s,
\]

where \( \alpha_1 \) and \( \alpha_2 \) are coefficients that determine how many times the duration of \( T_1 \) and \( T_2 \) is longer than \( T_s \). For example, for the Non-Chernozem zone of Russia, one can take \( \alpha_1 = 1.7 \) and \( \alpha_2 = 2 \).
Knowing the values of $\alpha_1$ and $\alpha_2$ from (5) and (6), we obtain the SC and HTC compositions interconnected through $T_P$. The inverse problem can also be solved, knowing the capabilities of the existing HTC ($T_1, T_2$), to determine the composition of the SC.

$$N^1 = x(\gamma) \cdot S[T_P(\beta \alpha_2 - \beta \alpha_1) + t_2^0(\alpha + \beta - 1)]^{-1},$$

$$M = x \cdot S/T_s.$$ (11) (12)

Varying $T_P$ within the permissible agrotechnical limits for a given zone, the most rational compositions of SC and HTC are found. The inverse problem can also be solved: knowing the capabilities of the existing HTC ($T'_1, T'_9$), determine the composition of the SC. For the Non-Chernozem zone of Russia, Acros 560 combine harvesters are used as HTC with $x(\gamma) = 0.036\gamma + 0.096$; for a SC, the value of $x$ depends on the composition of the machine-tractor aggregate (MTA) (Table 2).

**Table 2.** The value of $x$ to determine the composition of the SC.

| The composition of the aggregate | Cultivator KPP-2.2 with a tractor |
|----------------------------------|----------------------------------|
|  | T-150 | MTZ-1221 | MTZ-80 |
| SZP-3,6 seeding planter with tractor | | | |
| T-150 ....................... | 0.023 | 0.036 | 0.032 |
| MTZ -1221 | 0.41 | 0.48 | 0.44 |
| MTZ -80 | 0.56 | 0.59 | 0.38 |

**Table 3.** Values of shares of $\alpha_{\text{min}}$ cultivating aggregates in SC.

| The composition of the aggregate | Cultivator KPP-2.2 with a tractor |
|----------------------------------|----------------------------------|
|  | T-150 | MTZ-1221 | MTZ-80 |
|  | | | |
| SZP-3,6 seeding planter with tractor | | | |
| T-150 ....................... | 0.37 | 0.50 | 0.43 |
| MTZ -1221 | 0.26 | 0.37 | 0.31 |
| MTZ -80 | 0.36 | 0.44 | 0.37 |

If in SC cultivators are aggregated with MTZ-80 tractors, and seeding planters with T-150, then $x = 0.032, \beta_{\text{min}} = 0.37$ (Table 3).

With the existing fleet of combines in the Non-Chernozem zone ($\alpha = 0.6$ and $\beta = 0.8; \alpha_{\text{min}} = 0.4$ and $\beta_{\text{min}} = 0.6$) there are 5.4 combines per 1000 ha [7]. The duration of sowing spring grain $T_s = 9$ calendar days at $\alpha_1 = 1.7; \alpha_2 = 2 (T_1 = 15, T_2 = 18, t_2^0 = 4)$. Therefore, the numerical composition of the SC and the HTC agreed on the duration of the work is as follows:

$$M = 0.0036S;$$

$$N^1 = (0.0019\gamma + 0.0051)S.$$ (13) (14)

With optimal loading of all service subsystems, i.e. at minimal losses from machine downtime of complexes; their scope of work is 3000 ha. In this case, the optimal SC composition is 11 MTA (4 cultivators and 5 seeding planters), and the HTC at ($\gamma = 0.8$) - 8 combines.

An assessment of the functioning of the complexes should take into account the activities of all subsystems for the implementation of the work plan. The work intensity coefficient $K_{\text{wic}}$ equals to the ratio of the amounts of actually performed work (points) to the planned ones, it can serve as such an assessment of the daily work of the complex.

$$K_{\text{wic}} = \frac{\sum_{i=1}^{\nu}(1-\delta_i)S_i' t_i (e_i^j + u_i^j)N^{-1}}{\sum_{i=1}^{\nu}t_i (e_i^j + u_i^j)},$$ (15)
where $\delta_{jk}$ - share of crop losses on k-th day at j-th work;

$S_j$ - total real daily output of all machines $N_j$ at the j-th work, ha;

$\varepsilon_j$, $\varepsilon_j'$ - factors of complexity and importance of the j-th job, respectively;

$u_j$ - productivity on the j-th type of work, t/ha. The average work intensity coefficient $K_{wi}$ can be used for an overall assessment of the work of the complex for the entire harvesting cycle of work ($T_{\text{hav}}$).

$$K_{wi} = T_{\text{hav}}^{-1} \cdot \sum_{k=1}^{n} K_{wic}$$

The coefficients $K_{wic}$ and $K_{wi}$ can be used when summing up the work.

2. Conclusions

- To minimize grain yield losses, the numerical composition of planting and harvesting complexes should be linked through the duration of their work.
- Potential capabilities of planting and harvesting complexes can be realized only with the optimal composition of all subsystems of their service in accordance with the work plan of the agricultural enterprise.
- Process improvement paths identified on planting and harvesting crops. As an optimal option, the option of maximum use of the time used to change machine and tractor complexes due to the introduction of new organizational and technical forms was chosen.
- A mathematical model has been developed that allows choosing effective compositions of planting and harvesting complexes in the production of grain crops, both at the level of the agricultural enterprise and at the regional level.

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