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ENGINEERING MANAGEMENT OF FORECASTING THE TIMING OF COMBINE HARVESTING AND POSSIBLE LOSSES OF GRAIN CROPS

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Abstract

Direct combining of grain crops is possible when the grain is fully ripe. This is due to the physical and mechanical properties of the grain, which hardens when fully ripe, its shape and size become characteristic of a given crop and variety. The moisture content of grain in the phase of full ripening is in the range of 20-17% and below. The color of the plant is straw, the stems are brittle, the grain is easily threshed. At full ripening, the accumulation of dry matter in the grain is completed. In the future, for a very limited period, the mass of grain remains constant, and then decreases, since under the influence of external conditions, the grain loses part of its nutrients, that is, the so-called period of grain over ripeness, or overstaying of the grain mass on the vine, begins. During this period, the grain reduces its commercial, biological, flour-grinding, physical and mechanical qualities, crumbles easily, and in rainy weather it sprouts in the ear. With a long overstay, both the grain yield and its quality are significantly reduced. The crop, variety, natural and climatic conditions during the harvesting period or the zone of growing grain crops affect the amount of grain loss when harvesting is delayed.

Key words:
analyze, engineering management, forecasting, combine harvesting, grain crops.

Introduction

It is necessary to think about the harvest not in June (Zubko *et al.* 2018), but in winter, according to the principle "prepare the sleigh in the summer (Huang *et al. 2017*), and the cart in the winter." (Tihanov *et al.* 2021). Over the past few years, grain growers in Ukraine have collected record grain harvests (Nazarenko *et al.* 2021), and in terms of the number of exports, we are among the top three leaders, second only to the USA and the EU (Tryhuba *et al.* 2019).

This indicator can be considered a success (Hafezalkotoba *et al.* 2018). However, qualified specialists believe that grain on the market is only a raw material (Romaniuk *et al.* 2018). And real value-added products are products, including livestock products (Kuzmich *et al.* 2021). Who earns from the sale of grain as a raw material? Just not manufacturers (Radhakrishnan *et al.* 2012). The euphoria from the gross harvest pushed into the background the problems that accompany domestic producers: the ability to buy modern combines, the cost of fuels and lubricants and their derivatives are crop losses during combining (mechanical and biological) and the quality of the harvested crop (Xavier *et al.* 2020).

More than 50% of the harvested early grains are forage products, the cost of which per ton is much cheaper than food varieties (Baerdemaeker & Saeys, 2013).

The main cause of mechanical losses behind the harvester and thresher is the service life and technical condition of the combines, and the cause of biological grain losses is the number of combines, their technical condition and, accordingly, seasonal loads (Zagurskiy *et al.* 2018). For comparison: in Germany, for more than ten years, the seasonal load on the combine has been 33 ha/season, in the USA – 68 ha/season (Wang *et al.* 2021). Therefore, in developed countries, large agricultural producers determine the pace of harvesting the grown crop not through the number of combine harvesters, but taking into account the capabilities of granaries to clean and sort grain crops for further storage (Ratushny *et al.* 2019).

Formulation of problem

The problem of reducing grain losses has always been and remains relevant for agricultural producers (Pisarenko *et al.* 2019). Considering that grain crops are the main agricultural products of Ukraine, forecasting and control of grain losses during harvesting are essential measures. Often, managers, farm specialists, farmers are concerned about current economic problems, underestimate the significance of possible losses, and therefore do not always calculate and predict them, but prefer to control the losses that have already been made (Baumann *et al.* 2011).

In production activities, agricultural producers can use various experimental and theoretical methods for determining the yield (Rogovskii, 2020a). The first, experimental, is the calculation as a result of the completion of a certain technological process (Palamarchuk *et al.* 2021). The second is a calculated forecast of permissible biological losses for a particular crop, taking into account the indicators of the agrobiological and technical subsystem of the technological process in the conditions of a particular farm, district, region (Kalinichenko & Rogovskii, 2017).

For spike crops, the greatest losses are from the 8th to the 15th day after the onset of full ripeness of the grain, before and after this period, daily losses are less (Rogovskii, 2020b.).

Grain losses are divided into mechanical and biological. In the general case, mechanical losses are the result of violations of technical and technological adjustments, adjustments of combine harvesters and non-compliance with harvesting technology: movement speed, supply of grain mass to the threshing machine, and others. Biological factors are the result of a violation of the timing of harvesting and depend on the time factor (Rogovskii & Titova, 2021). Mechanical losses are calculated after harvesting, while biological losses can be calculated and predicted even before it starts (Baerdemaeker & Saeys, 2013).

Components of mechanical losses under threshing combines under economic conditions vary widely depending on harvesting conditions and operating modes (Wang *et al.* 2021). In most cases, losses from uncherished straw and chaff are 0.1-0.3%, and losses from free grain are 0.2-0.7% and 0.4-0.7%, respectively. The level of losses behind the header fluctuates when harvesting wheat from 0.7% (lodging - 3%) to 2.5% (50%), when harvesting barley – from 0.8% (3%) to 4.1% (65%). With the help of observation, it was revealed that the harvester ensures the collection of grain with losses that are allowed by agricultural requirements (1%) with lodging up to 10%. The level of grain grinding when harvesting wheat and barley does not exceed 1.5% (Rogovskii *et al.* 2019).

Up to 10-12% of grain is lost as a result of unsatisfactory mowing and picking up, improper regulation of working units and assemblies, violation of operating modes or careless control of the technological process by combine operators, their low qualification. If the harvester is technically sound, the units and mechanisms of the harvester, the threshing apparatus and separating organs are correctly adjusted, the possible places of losses and joining of units are completely sealed, the rules for mowing and picking are observed, then all types of grain losses behind the combine during threshing in total should not exceed 4 t/ha and more – 60 kg/ha (Zubko *et al.* 2018).

Purpose of research

The purpose of the research presented in the article was to search for analytical provisions for predicting the timing of combine harvesting and possible losses in the crop of grain crops.

Research results and discussion

Mechanical losses of grain are divided into (Fig. 1):

– direct (non-returnable, which remain in the field or on the way to the storage);

– by-products (grain damaged during threshing).

Direct losses are the actual losses for:

– reaper (loose grain, cut ear, uncut ear);

– pick-up (loose grain, cut ear);

– cleaning (free grain in the chaff);

– straw walker (free grain in straw);

- thresher (under-threshed in straw and chaff);

– through slots and seals (free grain).

Collateral losses

- those that appear as a result of:

– microdamages (grinding, flattening, peeling);

– microdamages (damage to the embryo, grain shell).

According to the technical characteristics, modern grain harvesters allow up to 1.5% losses of the world's leading combine-building companies and up to 2.5% of domestic ones. As studies and many years of production practice show, the magnitude of technological losses is influenced by many objective and subjective factors, in particular, the agrobiological characteristics of the grain mass, the quality indicators of technical and technological adjustment. Agrobiological characteristics are defining and dominant, so they must be taken into account when planning harvesting and predicting losses.

Experimental method for determining technological losses grain when combining is regulated taking into account the harvesting technology - separate combining with a pick-up and direct combining with a header.

The total losses during separate combining are defined as follows:

$$P_r = P_p + P_m, \tag{1}$$

where P_p – losses after the pick-up;

P_m – losses after the thresher.

The total losses in direct combining are defined as follows:

$$P_p = P_z + P_m, \quad (2)$$

where P_z – losses behind the header.

Thresher losses are defined as the sum of:

$$P_m = P_{nk} + P_{ss} + P_{np} + P_{sp}, \quad (3)$$

where P_{nk} – the loss of unthreshed spikelets in the straw;

P_{ss} – loss of free grain in the straw,

P_{np} – losses from under threshing of grain in the chaff,

P_{sp} – loss of free grain in the chaff.

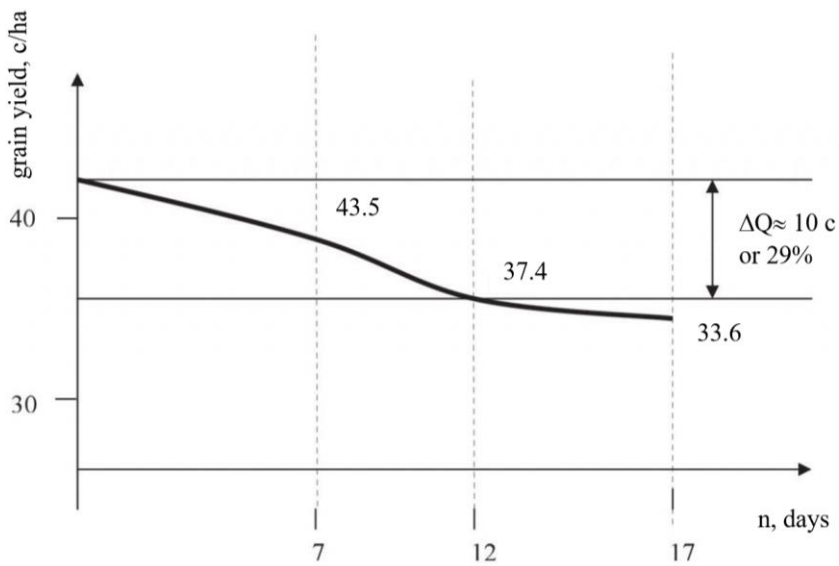

Figure 1. Dependence of agrobiological losses of Odesskaya-3 wheat on the duration of harvesting.

Of great practical importance for the planning of harvesting work are the features of the passage of the phases of grain development. The duration of the development phases and the nature of the passage are very variable and are characterized not only by the species and varietal characteristics of the culture, but also to a large extent by external natural conditions. Thus, the duration of the wax maturation phase in the southern and steppe regions in hot and dry weather can be reduced to 3-4 days, and in humid regions it lasts up to 20 days. After full ripening, the period of over-ripening of the grain begins. During this period, the grain reduces its biological, technological, biochemical, physical and mechanical, sowing and nutritional qualities, easily crumbles, which ultimately leads to a sharp decrease in the biological yield.

Harvesting of each crop must be completed 5-7 days after the full ripeness of the grain.

Mechanical losses are dominant in conditions when the seasonal load on the harvester does not exceed the standard or corresponds to 10 days of work. In conditions of exceeding the standard load, biological losses are added to the mechanical losses, which can exceed the mechanical ones by 3-10 times.

The harvesting cereals, the optimal start of harvesting should be based on two limiting restrictions: biological and technical and economic. Biological harvesting restrictions must be started at the moment of reaching the maximum biological yield and completed in a very short time to prevent loss of grain from self-shattering and reduction of its quality from overstaying or being in windrows.

The technical and economic limitation is the availability of the necessary fleet of harvesters, transport, fuel and the ability of farms to accept grain for storage.

Therefore, biological and technical and economic constraints must be optimally balanced in order to harvest the maximum yield. Science has proven and practically confirmed that the highest yield of winter wheat and rye can be obtained by harvesting in a separate way in the middle and at the end of wax maturation with a grain moisture content of 28-30%, which is considered the most favorable for mowing grain mass into rolls.

Each grain crop, due to its biological characteristics, has its own optimal time for the start of mowing into rolls. The duration of mowing into rolls is 3-4 days. The optimal period is considered to be 4 days for all grain crops. The separate method is effective if swaths are picked up 5-6 days after mowing and completed in 7-8 days. Delaying the beginning of the selection significantly reduces the yield. The onset of the phase of full ripening of the grain means the transition to direct combining.

Direct combining of grain crops is possible when the grain is fully ripe. This is due to the physical and mechanical properties of the grain, which hardens when fully ripe, its shape and size become characteristic of a given crop and variety. Humidity of grain in the phase of full ripening is in the range of 20-17% and below. The color of the plant is straw, the stems are brittle, the grain is easily threshed. At full ripening, the accumulation of dry matter in the grain is completed. In the future, for a very limited period, the mass of grain remains constant, and then decreases, since under the influence of external conditions, the grain loses part of its nutrients, that is, the so-called period of grain over ripeness, or overstaying of the grain mass on the vine, begins. During this period, the grain reduces its commercial, biological, flour-grinding, physical and mechanical qualities, it crumbles easily, and in rainy weather it sprouts in the ear. With a long overstay, both the grain yield and its quality are significantly reduced.

The crop, variety, natural and climatic conditions during the harvesting period or the zone of growing grain crops affect the amount of grain loss when harvesting is delayed.

The influence of the variety on the amount of grain loss during overage is shown by numerous experiments and practice. Grain shedding of the Mironovskaya Yubileinaya variety when harvested 10 days after full ripening was 4.8 c/ha, and Bezostaya – 1-3.3 c/ha. In the Krimchansky variety plots of the Dnepropetrovsk region, when harvesting 7 days after the ripening of the Odesskaya-51 variety, the losses amounted to 0.3 c/ha, and with a 15-day overage, respectively, 4.7 c/ha (with a yield of 57.6 c/ha). In 2020, in the Valkovsky variety plots of the Kharkov region, the yield of the Odesskaya-3 variety during the period of wax ripeness was 45.1 centers per hectare, and 7 days after the start of harvesting – 43.5 centers per hectare, after 17 days – 33 centers per hectare.

The indicators of grain shedding of various crops, depending on the timing of harvesting, are shown in Table 1.

Table 1. Grain losses of different crops depending on the timing of harvesting

Duration of cleaning, days.	Winter rye		Winter wheat		Spring wheat		Spring barley		Oats	
	Loss of grain during harvesting									
	c/ha	%	c/ha	%	c/ha	%	c/ha	%	c/ha	%
4-7	1.0	3.2	1.4	4.1	1.0	6.7	0.7	2.8	4.4	16.1
8-10	2.4	8.4	3.0	9.1	2.1	10.5	0.8	3.0	5.9	21.6
11-13	3.0	14.2	4.9	16.2	2.7	17.1	2.2	8.7	7.3	26.8
14-16	3.8	15.2	5.0	17.3	3.3	29.7	4.0	15.7	7.8	28.6
17-20	5.5	18.4	8.5	27.3	5.4	32.1	5.6	24.2	8.4	3.8

Recently, specific indicators have begun to be widely used. So, to characterize the dependence of the grain loss on the duration of harvesting, an indicator of the grain loss for each day of overstaying or for each hour of overstaying after the onset of full ripeness of the grain is used (Table 2).

Table 2. Losses of grain during harvesting after the onset of full ripeness for each subsequent day or hours of rest.

Crops	Average values of grain loss.			
	kg/ha		% of the harvest	
	per day	in an hour	per day	in an hour
Winter rye	26.6	1.108	1.02	0.0425
Winter wheat	36.2	1.506	1.15	0.0479
Spring wheat	21.6	0.901	1.14	0.0475
Spring barley	29.2	1.217	1.24	0.0517
Oats	35.9	1.496	1.38	0.0575
Average values of grain	30.0	1.251	1.21	0.0501

The generally accepted method is considered to be a method for determining losses by harvesting time from one initial actual yield at full ripeness of the grain, which gives the amount of losses with increasing rates. Unfortunately, with this method it is impossible to trace the dynamics of loss measurement from day to day.

Mathematical processing of data on grain losses at different harvesting periods made it possible to establish the following pattern: for spike crops, the greatest losses are from the 8th to the 15th day after the onset of full grain ripeness, before and after this period, daily losses are less. This once again confirms the conclusion that the harvesting of each crop must be completed within 5-7 days of harvesting after the full ripeness of the grain. The dynamics of grain losses of different crops for each day of harvesting is shown in Fig. 2.

Optimal technologies include the choice of such operations and techniques that provide a minimum of losses in relation to the maximum yield. The operation of machines during the performance of technological processes is regulated and determined by qualitative, quantitative and temporal indicators. Qualitative indicators during harvesting are characterized by the height of the cut, the quality of threshing and cleaning, harvesting of the laid grain mass, etc. Quantitative indicators are fuel consumption per unit of production, hourly, daily, seasonal productivity. But time parameters have the greatest influence on crop losses. Premature or late deadlines for the implementation of certain types of work lead to a shortage or significant crop losses. The most rational technological methods and modes of operation,

The generalized dependence of yield losses on the duration of harvesting and grain moisture content in the ear is shown in Fig. 3.

Studies conducted during the Soviet Union and abroad have shown that when harvesting grain, losses can reach 30% of the grown crop and are mainly a consequence of the timing of harvesting, the peculiarity of harvesting fallen and clogged grain arrays, and the technological imperfection of harvesting equipment. Therefore, the main content of agricultural technologies is the timely execution of each operation. Empirical dependences are given in the literature for calculating crop losses from the time factor. The level on the final day of cleaning is determined by the formula:

$$P_b = a \cdot n \cdot 2/3 + b \cdot n \cdot 1/2 + c, \quad (4)$$

where P_b – biological crop losses;

n – the duration of harvesting, days;

a, b, c – coefficients depending on the varieties and the agrotechnological state of the crop and weather conditions during the harvesting period: a = 0.002–0.061; b = 0.065–0.621; c = 0.0003-0.7001.

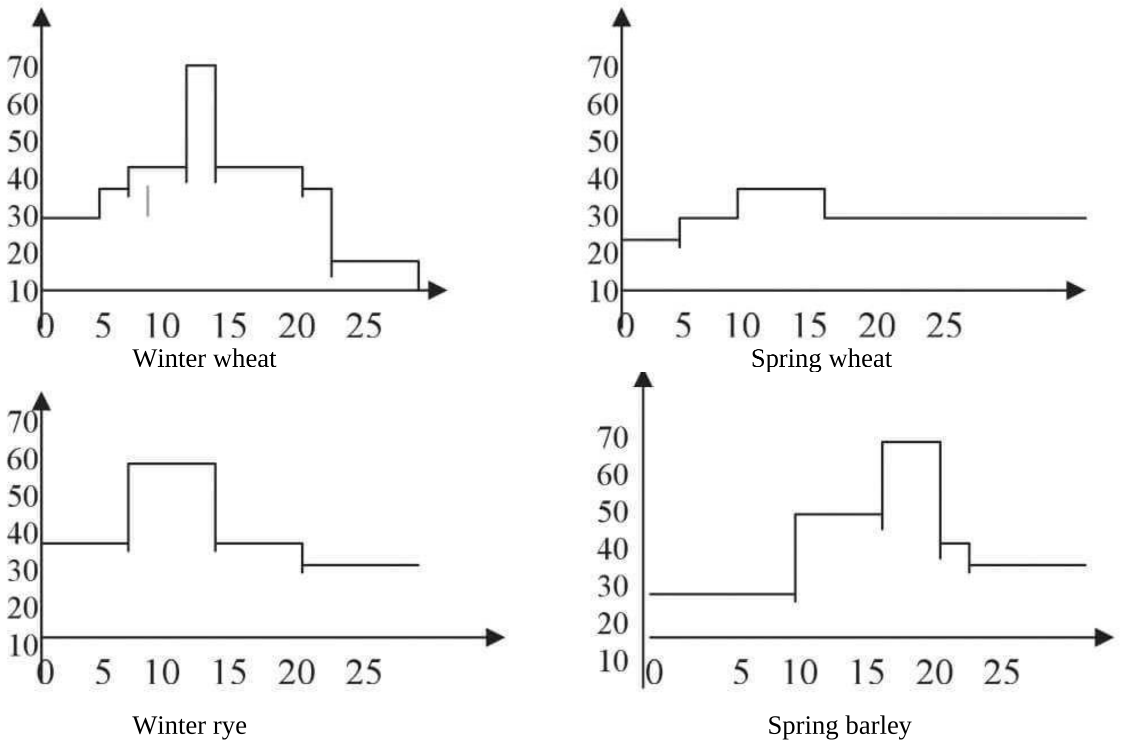

Fig. 2. Dynamics of grain losses of different crops for each day of harvesting.

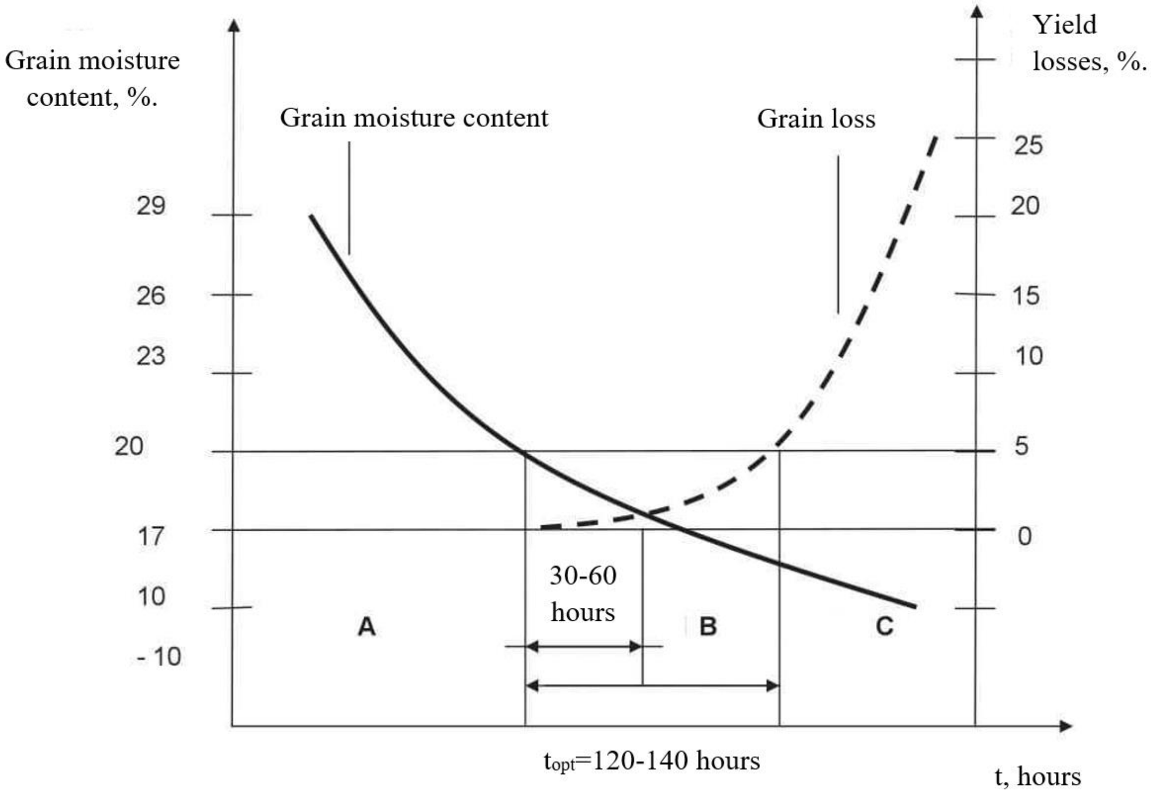

Fig. 3. Generalizing dependence of crop losses on the duration of harvesting and moisture content of grain in the ear: A – period of separate combining; B – the period of direct combining with the minimum allowable losses; C – the period of direct combining with increasing losses.

D. Hunt from the University of Iowa proposed a coefficient K (dimension 1/year), which allows taking into account the reduction in yield due to a delay in the operation by 1 hour against the optimal technological time. According to Hunt, the K coefficient for corn and soybeans is 0.0003, basic tillage is 0.00005, cultivation is 0.0002, grain harvest is 0.0003, soybean is 0.0007, hay is 0.0005, harvesting silage crops – 0.0001.

$$\mathrm{C} = K \cdot A \cdot V \cdot U, \quad (5)$$

where A – the land area, ha;

V – the expected (without loss) yield;

U – the unit cost of the crop.

The total losses in this case are:

$$\mathrm{C}_x = C \cdot T_0, \quad (6)$$

where T_0 – the total number of hours of delay in harvesting for the calendar period of harvesting.

If the machine works on time, but its productivity is insufficient to complete all the work in the optimal time, then the losses from crop losses will be:

$$\mathrm{C}_y = K \cdot A \cdot V \cdot U \cdot (T_v - 1)/2, \quad (7)$$

where T_v – the number of hours of operation of the machine in this operation.

All modern combine harvesters of the leading manufacturers are equipped with an automated control system of technical indicators and technological parameters of the operation of the main units, systems, mechanisms of the combining technological process. In the conditions of real operation, if the automated control system fails, its performance may not be restored for various reasons. Experimental studies were carried out in order to demonstrate the influence of the operability of the automated control system on the quality of the technological process. In the process of research for combines with working and non-working of automated control system, losses and grain crushing index were measured. In the first and second groups there were 19 combines. The research results revealed that for combines with a working of automated control system, the level of mechanical losses was 1.94%, and for combines with non-working of automated control system, these figures amounted to 5.18% and 2.3%, respectively. The research results showed that ASC significantly affects the quality of the grain harvesting process.

Calculations using the above formulas show that for a harvesting period of 270 hours at average values of the coefficients (a, b, c), relative losses can reach 6.7% of the harvested mass, and at the limit values of the coefficients – 13%. That is, losses during gross harvesting can reach 5-6 million tons.

If we accept for calculations the relative losses given in Table 1, then the average biological losses will be 28.8% of the gross harvest.

The control of mechanical losses of grain is a tactical task of engineering management. In organizational terms, harvesting quality control is a set of methods, means of control and performers interacting with the objects of control according to certain rules. Therefore, the problem of reducing losses and obtaining high-quality grain must be considered as an integrated system at all stages of the technological process of harvesting grain crops. The concept of harvesting quality must be considered not only through the quality of products (grain and non-grain parts), but more generally, through the quality of mechanized work in individual operations. The work of each machine or group of machines must be evaluated according to agrotechnological requirements through a generalized indicator – the level of mechanical and biological costs.

Mechanical losses are the dominant standard seasonal load on a combine harvester of a certain series, model and modification, which can be assembled in up to 10 days. When the seasonal load on the harvester exceeds the standard by 1.5 or more times, biological losses are added to the mechanical losses, which can exceed the mechanical ones by 3-10 times. Biological loss prediction is a strategic task of engineering management.

Conclusions

In the process of research for combines with working and non-working of automated control system, losses and grain crushing index were measured. In the first and second groups there were 19 combines. The research results revealed that for combines with a working of automated control system, the level of mechanical losses was 1.94%, and for combines with non-working of automated control system, these figures amounted to 5.18% and 2.3%, respectively. The research results showed that automated control system significantly affects the quality of the grain harvesting process.

Mechanical losses are the dominant standard seasonal load on a combine harvester of a certain series, model and modification, which can be assembled in up to 10 days. When the seasonal load on the harvester exceeds the standard by 1.5 or more times, biological losses are added to the mechanical losses, which can exceed the mechanical ones by 3-10 times. Biological loss prediction is a strategic task of engineering management.

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