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Analysis and forecast of performance characteristics of combine harvesters

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Abstract. This article presents results of an experimental research of qualitative indicators of the modern combine harvesters (Case IH Axil Flow 8230, MasseyFergusonMFT7, JohnDeereS680i, ClaasLexion760, NewHolland CR9.80) used for winter wheat harvesting. Based on the results obtained, determination was made regarding the productivity of combine harvesters on the field, fuel consumption, and field conditions influence the grain loss and grain damage caused by a harvester. When conducting the experimental research of a combine's performance on the field, a study of the effectiveness of the combine JohnDeereS680i was made on different modes. A program 'Machine Unit', designed by the authors, was used for the determination of productivity, fuel consumption and quality indicator for harvesting.

Key words: combine harvester performance, fuel consumption, chaff in a grain tank, post-harvest losses, loss of grain, grain damages, plant residues.

INTRODUCTION

Due to the growing population and the simultaneous increase in food demands, the role of mechanization in agriculture is essential (Hafezalkotob et al., 2018). Agribusiness entails a large number of inherent risks associated with natural and biological phenomena (Mimra et al., 2017). Therefore, for the purpose of business development, producers of agricultural products focus all the material and physical resources on determining the ways to increase the gross harvesting of products, and improve its quality indicators compared to previous periods as well as products of competing companies. However, it is not enough to grow the crops with high level biological parameters (as for winter wheat: the yield, weight of 1,000 grains, grain unit, glassiness, gluten, mass fraction of protein, germinative power and germination of seeds (Kirpa, 2010). In addition, it should be stated that grain loss is an inevitable part of the working process of a combine harvester, which is influenced by a wide range of parameters (Liang et al., 2017). Usually, the simultaneous minimization of grain losses and the operation time of combine harvester requires the optimal selection of the construction and operating parameters for the straw walker unit, whereas the phenomenon of grain separation and its determinants depending on these parameters are not yet well understood (Myhan & Jachimczyk, 2016). Consequently the challenge to gather a biological harvest of the plant in the most efficient way still.

The introduction of new technologies into the agricultural production requires constant upgrades of the machines (Liang et al., 2017; Hafezalkotob et al., 2018). Due to the reduction of the existing combine harvester park, physical depreciation of the machines, their obsolescence, increase in number of the broken machines, as well as an increase in the average load on the machine, it is important to choose the combine harvester that meets the conditions in the sector best (Maslacq et al., 2016). Upgrading the machines brings long-term positive results in technical and economic areas (Mimra et al., 2017), so when choosing a combine harvester one needs to analyse both the technical characteristics and the results of field trials.

A combine harvester needs to be a high-tech one in order to deliver high productivity with minimal crop losses, damage and minimal expenses on maintenance and repairs of a machine (Kavka et al., 2016; Špokas et al., 2016). If a combine harvester suffers physical and moral obsolescence, it is inappropriate from an economic standpoint to use such a combine (Mimra & Kavka, 2017).

The main requirements for crop harvesting include optimal agronomic conditions, while ensuring minimum loss of products and appropriate quality of grain, as studied for example by Kehayov et al. (2004) and by the Tymchuk et al. (2015a). It is necessary to exclude losses resulted from the mass standstill, losses caused by combine harvester passing and other losses associated with it caused due to the mechanical damage of grain (Huang et al., 2017). These losses are the result of varying realization degrees of the seed biological potential all over the total field area (various conditions for YPF consumption, level of humidity and nutrients volume). Additionally, losses increase with non-compliant adjustments of the combine harvester, which may not always provide an effective work of the harvester, with a late service maintenance and a late replacement of units, which are responsible for threshing, adjustment of gaps on a threshing device of the combine within an acceptable error margin (Tymchuk et al., 2015b).

Such a loss of winter wheat causes weeding of the field with sprouted grain and an increase in the pests and diseases population, which inevitably leads to additional costs required for alleviating relevant phenomena. In addition, minimum harvesting time needs to be guaranteed for crops gathering with a special consideration of weather conditions at the selected harvesting time. Humid weather not only stops a process of harvesting, it also leads to an active spread of diseases which causes the bud darkening, and an increase of a contaminated grains share and their germination within a year (Cherenkov et al., 2011). Thereby, it decreases purchase price for the produce.

Based on the results of the field research executed by Kirpa (2010), it was found that depending on timing and duration of a harvesting process, as well as harvesting quality assurance (combine adjustments, combine setting modes, control of work performed by the equipment), losses may reach up to 16–18% of a biological harvest (Kirpa, 2010). One of the ways to increase the gross harvesting is to reduce losses by securing high food, feed and seed qualities during gathering, transporting, post-gathering processing and storing (Huang et al., 2017). This can be attained by reducing the duration of the crop gathering to a minimum threshold, not exceeding a five-day period (Demko, 2011). The reason for this is that after the fifth day there is a significant decline in glassiness quality and a reduction in weight of 1,000 grains (Demko, 2011). A 10–20 days delay results in a significant reduction of the mass fraction of protein and a gluten quality as described by Cherenkov et al. (2011).

When harvesting, it is important to ensure effective distribution of plant residues on the field combined with a minimal fuel consumption and a maximum level of the combine harvester productivity (Gürsoy et al., 2015). Seed germination and spread of rodents and diseases depends on a stubble height (Kumhála et al., 2005), a grinding degree of the straw remains (Kviz et al., 2015) and an equality of distribution of plant residues on the field surface (Buryakov & Skoblikov et al., 2017). A grinding device of the combine harvester should provide a high-quality straw grinding – 90% of all pieces should be shorter than 80 mm (Kumhála et al., 2002). Quality of the distribution work is characterized by the residues distribution heterogeneity at a high work speed, which is a result of increase in quantity of material being delivered to a combine harvester. The more material gets to the harvester per time unit; the worse the equality of distribution of the residues becomes (Kvíz et al., 2015). This is caused by the inconsistencies in using mass and engine power of the combine harvester, area of threshing cylinder and a cleaning system (Makarenko, 2014).Fuel consumption is a very important parameter as it directly correlates with the economy of agricultural machines use (Vasylieva & Pugach, 2017).

Therefore, a profitable farming system is expected to minimize the fuel consumption by the machines used in agriculture (Gürsoy et al., 2015), because cost of fuel cover 19–30% of total costs during the harvesting (Mimra & Kavka, 2017). As such, further research of modes and parameters of work in the actual field conditions is necessary.

For the efficient operations in agriculture, it is advisable to conduct a study of the performance effectiveness of a combine and to identify the relevant risks while developing a business plan (Kavka et al., 2016). The strategy for harvesting is significantly influenced by climatic zones and the terrain. Thus, a research of factors of work effectiveness of combine harvesters should be conducted in each region. Reliable data is required for developing a harvesting strategy (Špokas et al., 2016).

The goal of this study was to define qualitative factors and to analyse performance characteristics of combine harvesters during gathering early grain crops (wheat), to determine the productivity of harvesters and the actual fuel consumption for specific soil and climatic conditions. The research also aimed to evaluate the study methodology of technical factors in a production environment, using a combine John Deere S680i with a John Deere 630f reaper.

Table 1. Technical Characteristics of the Studied Combine Harvesters

	Option	J D S680i	C IH 8230	N H CR9.80
Engine	The number of cylinders, units	6	6	6
	Engine, cm³	13,500	12,900	12,900
	Nominal power, HP	473	476	489
	Maximum power, HP	547	516	530
Rotor	The location of a rotor	Longitudinal	Longitudinal	Longitudinal
	Number of rotors, units	1	1	2
	Diameter, mm	762	762	559
	Length, mm	3,124	2,623	2,638
	Rotation frequency, RPM	380–1,000	220–1,180	200–1,050
	The frequency of rotation of a gear, RPM	210–550		
Separation	The main metal area under the drum, m²	1.1		
	The area of the threshing and separation, m²	1.54	2.98	3.06
	The total area of a cleaning system, m²		6.5	6.54
	Fan speed, RPM	620–1,350	300–1,150	200–1,050
	Threshing system	EvenMax – Active returning of threshing returns with an additional beater	Three-rubbing drums mechanism	Roto-Tresh-double
Bunker	The capacity of the grain tank, m³	14,100	12,330	12,500
	Upload speed, L sec^{-1}	135	113	126
Fuel tank	Capacitance, L	1,250	1,000	1,000
Price (euro)		290,000	255,000	280,000

MATERIALS AND METHODS

Harvesting agricultural crops is one of the most responsible and energy-intensive production processes of the crop production. In the general cost structure of crop production in Ukraine, harvesting requires 31–50% of energy and 45–60% of labour costs (Makarenko, 2014). Given a steady increase in cost of equipment and petroleum, oils and lubricants, an important task is to ensure the minimum cost of the harvesting process. In addition, it is important to preserve accumulated energy during the whole period of vegetation. The other factor for consideration is ensuring a minimum loss during threshing and minimal injury of the grain. Loss of grain during threshing and separation, damage of grain, fuel consumption, and combination of productivity are considered to be the basic criteria for the evaluation of the combine harvester performance in the field. All of the above criteria are essential and closely related to work conditions of harvesting (Špokas et al., 2016). This study was conducted in the field, using combine harvesters Case IH Axil Flow 8230-2, MasseyFergusonMFT7, JohnDeereS680i, ClaasLexion760, NewHolland CR9.80,used in the 'Palmira LLC', a cluster of groups of companies 'Kernel' in the Privitne village (Poltava region, Ukraine) from July to August 2016. Technical characteristics of the studied combine harvesters can be found in Table 1.

When analysing the performance of combine harvesters, the following criteria and methods of evaluation of the quality of the studied machines were used (Table 2):

Table 2. Criteria and Methods of Evaluation of the Quality of the Studied Machines

1.	Crop that is being harvested	− Winter wheat
2.	Range of a crop productivity	− 6–9 t ha^{-1}
3.	Cut height of a stubble	− max 12 cm
4.	Fuel consumption	− Chronographic measurement
5.	Productivity	− Chronographic measurement
6.	Quantity of broken grains	− Laboratory analysis
7.	Loss after passage of a combine	− Mobile laboratory
8.	Distribution across the width of the reaper	− Even, with a full coverage of the width of the reaper

Chronographic Measurement

Study of the main technical and economic indicators of the combine performance was conducted by the means of time chronograph and timekeeping methods to meet the requirements of the application methods of timekeeping according to the norm GOST 24055-88 (GOST 24055-88(1988): Methods of operational and technological evaluation. General; Moscow, USSR, 1988).

The observation was carried out for each item of separate technological operations. The following devices were used:

- A mechanical stopwatch according to GOST 5072-79 (GOST 5072-79 (1979): Mechanical second moments. Technical conditions; Moscow, USSR, 1979), 3.0 accuracy class;
- A measuring roulette with a 50 m length according to GOST 7502-98 (GOST 7502-98 (98): Measuring metal tapes. Specifications; Moscow, Russia, 2006), 3.0 accuracy class;

– A measuring ruler with the length of 3.5 m as per GOST 427-2009 (GOST 427-2009 (2009): Linear measuring metal. Specifications; Kiev, Ukraine, 2009);
– A graduated measuring probe, with the length of 1 m according to GOST 427-2009.

Time was monitored using a stopwatch with a precision of up to a second; the average length of field parcels was measured with an accuracy of 10 m; a width of coverage by a machine – accuracy of up to 1 cm; the level of fuel in the fuel tanks – up to 1 mm.

Time keeping was carried out with consistent tracking and noting of time spent on all sorts of actions according to the mechanized technological method of harvesting winter wheat along with the measurement of the amount of work performed and the actual cost of fuel.

Time recording was held consecutively, starting with the preparation of a machine unit for work (technical maintenance). It combined the elements of technological process, its useful work in working mode, spending time on parking the unit in a working stroke for various reasons (technological, technical and organizational), on idling and turning around.

Data obtained from this research was included in an observations tracker. In the beginning of a work shift, time was recorded in the tracker. The beginning of a technological operation element was the end of the previous element. With a combination of several elements of operation, the longest of them was determined. The rest of the items were mentioned in the tracker as ancillary. In cases where the execution of some elements of technological operation took more time than per norm, the reason was noted in the tracker.

During the work of the machine, the length of time used for the operational element was measured and noted. If during the shift, one had to move from one area to another, both duration and distance of the relocation were noted. When evaluating the observations tracker, a determination was made regarding an average width of coverage by a machine unit, average working speed of the unit with a load, productivity of the unit per an hour of genuine work, and fuel consumption per 1 ha.

The average working width of coverage of the machine unit (Bp) was determined using the Eq. 1:

$$B_p = \frac{C}{n}, \ m, \tag{1}$$

where C is the width of the parcel area under cultivation during the observation, (*m*); n – the number of passes made by the machine unit.

The average operating speed of a machine unit (Vcp) was calculated using the Eq. 2:

$$V_{cp} = \frac{l_{cp.} \cdot n}{1{,}000 \cdot T_p} \ km\ h^{-1}, \tag{2}$$

where l_{cp} – the average length of parcels of the cultivated area (*m*); n – number of passes made by the machine unit; T_p – working time spent throughout a period of observation, (*h*).

Machine performance (W; ha h-1) was calculated using the Eq. 3:

$$W = \frac{A}{T}\text{, } ha\ h^{-1}, \quad (3)$$

where A – harvested area, *(ha)*; T – harvest time, *(hrs)*.

Research of Losses by Combine Harvesters

As a result, performed experimental methods were defined by technical standards related to the research of agricultural machinery and its subsequent quality testing, namely, by the technical standards OST 70.8.1-81(1982) (OST 70.8.1-81:Testing of agricultural machinery. Grain-harvesting machines. Program and test methodology; Moscow, USSR, 1981).

Determination of a Grain Yield

The yield of grain was determined by the results of weighing of grain selected for sampling for quality of machine work, including all types of losses, but excluding the addition of debris.

Equipment used during the determination:

- A sample collector (a truck, sacks 4 x 3, 5 x 4, 2 x 1.5 m);
- A spring dynamometer of a general purpose as for GOST 13837-79(1982) (GOST 13837-79: General-purpose dynamometers. Specifications; Moscow, USSR, 1982) with an increment of 1 kg within a measurements range of 0–100 and 0–200 kg;
- A moisture measurer of grain;
- A stopwatch;
- An electronic scale;
- A seeds divisor;
- A weighing bottle;
- A drying container;
- A collapsible boards;
- A mobile laboratory;
- A putty knife;
- Standard sacks and bags, size 20 x 30 cm.

Preparation for Selecting and Sampling

For sampling at 60 meters from the edge of the field, an area of the sowing plot was determined. The length of the parcel matched the length of the field rut– 1,020 m, of a rectangular shape. The width of the area allowed making selection of the samples from all combine harvesters that are being compared.

Before selecting a sample, a combine was set up at the optimal mode in accordance with the requirements of the test. The details of the mode parameters were noted in the notebook.

With every repetition of the experiment by the combine, the following thrashing products were selected for analysis: grain from a bunker; straw; chaff.

While unloading the grain, a sample with an average weight of 2–2.5 kg was selected within 5–6 rounds and placed in a bag for the analysis. Samples of straw and chaff were collected and placed in weighing bottle for analysis of humidity.

Straw, chaff and grain, collected from the site, were weighed on a scale with accuracy of up to 1 kg, and were labelled.

Sample analysis

When analysing grain in accordance with GOST 13586.3-83 (2009) (GOST 13586.3-83: Grain. Acceptance rules and sampling methods; Moscow, Russia, 2006), there are two bulk samples. The analysis was carried out according to GOST 13586.3-83 (2009).

A sample was divided into the following fractions: main grain, grain in ears and rinds, crushed grain, and an adulterant.

All fractions were weighed. Their percentage content was calculated with accuracy of up to hundredth percent share by the formula (4):

$$\Delta q = \frac{q_{1.} \cdot 100}{Q} \qquad (4)$$

where Δq_i – is the main content of grain or other factions; q_i – mass fraction in weight, (g); Q – mass of weight, (g).

The content of crushed and broken grain is determined in the percentage of grain in the grain mass in a sample.

The weight of 1,000 grains was determined according to GOST 10842-89 (89) (GOST 10842-89: Cereals, pulses and oilseeds. Method for determination of 1,000 kernels or seeds weight; Moscow, Russia, 2009), and results were recorded in the notebook. For each indicator of the grain quality, an average value of three experimental recurrences in each mode was calculated and recorded in the notebook.

Figure 1. Determination of losses after the passage of a combine on an area of 1 m^2.

Figure 2. Air blowing plant mass using the mobile laboratory

Determination of Quantity of Grain Lost

Losses in the process of harvesting were determined using the trays (Fig. 1) which were placed under a combine harvester. Mass, obtained after the passage of a harvester, was sorted out using a mobile laboratory (Fig. 2) and was weighed using the scales (Fig. 3). The results were noted in the notebook.

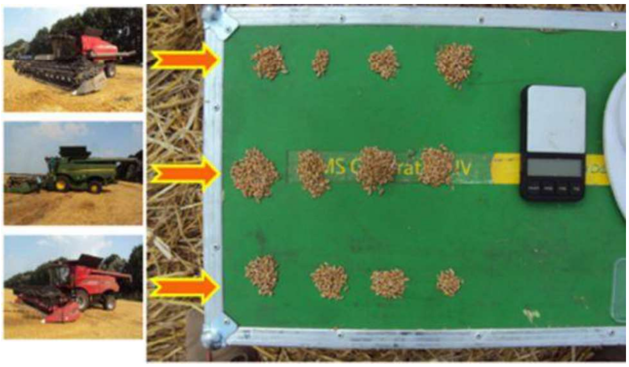

Figure 3. Determination of the quantity of grain losses after the passage of combine harvester.

The Determination of Broken Grain

After the sample weighing analysis for the detection of the micro damages, two samples of 100 pieces each were taken out of the whole grains. Each sample was placed in a paper bag, which had an indication of all the source data (the combine brand, date of collecting a research sample, number of an experiment and recurrence, etc.). Thus, every average sample had four selections for the test, totalling 400 grains.

Grains were inspected with a magnifying glass. Grains with a pushed out embryo, a defective embryo and an embryo with a damaged shell were separated.

Micro damages were calculated with an accuracy up to the tenth of a percent share. Losses through the gaps of a harvester were monitored thrice. At the end of the experiment, the grain was thrown on a shield, collected and weighed up to 1 g.

Modelling of Parameters and Operating Modes of the Combine Harvester

In the course of conducting an experimental research of the harvesters' performance on the field, a research was conducted related to work of combine harvesters on various modes of productivity, fuel consumption the indicator of the quality of collection. The research was based on the use of the programme 'Machine Unit', which was developed by the authors 'team under the scientific supervision of the professor I. Melnyk (Melnyk et al., 2015).

The first experiment was aimed at determining the dependency of the change in productivity and fuel consumption, when the working width of the reaper of combine harvesters is changed at the same speed.

In this situation a tool, which allows gathering data for processing, analysis and decision-making is crucial. Specifically, the attention should be given to a technique, which is used for obtaining information. The results of computational experiments should correspond to the results of chronographic observations in the production environment. The mathematical model and a computer program 'Machine Unit' was implemented in the Microsoft Excel namely to serve this purpose. The structure of the program is shown in the scientific study Melnyk et al. (2015).

The input data for calculation were technical characteristics of the combine harvester (a working width of a reaper, an operating speed, a bandwidth, an operating weight, an engine power, fuel consumption, a technical service system, the kinematic length of a machine, and the coefficient of machines reliability).

The outcomes of computational experiments were a study of performance, operating speed, coefficient of working moves and fuel consumption. Based on the theoretical calculation and the experimental research results of the above-mentioned indicators, it was determined that the difference in the results was within 2.5–4%.

RESULTS AND DISCUSSION

Purchase and maintenance of the agricultural producing equipment are the two most significant expenses in the agricultural production (Buckmaster, 2003). Therefore, it is important to choose the most optimal combine harvester. Under the real conditions, a combine should demonstrate the highest productivity with the lowest fuel consumption, minimal losses and grain damage (Vasylieva & Pugach, 2017).

A combine harvester is a machine that requires precise working settings and ensuring the optimum working speed (Beneš et al., 2015). Therefore, before the test, all of the machines had to be set respectively to the wheat type and working conditions.

The results of the productivity research according to chronographic data obtained in this research are listed in a Table 3. Performance results were received without taking into consideration the time needed for unloading a combine and a downtime related to a lack of transport, so only the time results related to actual work of a combine were taken into account.

Table 3. Performance Results According to Chronographic Data

A Combine Harvester + Reaper	Area, hectares	Actual working width of reapers, m	Speed of moving, km h^{-1}	Productivity of main time, hectares per hour	Rotations of the engine, RPM	Quantity of fuel, L	Yield, kg ha^{-1}	Humidity content, %
John Deere S680i +	17.15	9.14	5.2	**5.6**	2,050	319	7.07	12.8
John Deere 630f	9.29	9.14	5.0		2,050	191	7.36	10.7
Average value:	**26.44**		**5.1**			**510**	**7.22**	
CASE IH Axil Flow 8230 +	16.77	9.14	3.5	**3.7**	1,950	369	6.90	15
CASE IH 3020 Flex	9.41	9.14	4.0		1,950	235	7.20	12.5
Average value:	**26.18**		**3.8**			**604**	**7.05**	
CASE IH Axil Flow 8230 +	5.95	9.14	3.5	**3.7**	2,100	124	5.30	14.1
CASE IH 3020 Flex	4.72	9.14	4.0		2,100	104	7.20	10.8
Average value:	**10.67**		**3.8**			**228**	**6.25**	
Massey Ferguson MF T7 +	18.70	9.14	4.0	**3.6**	2,120	317	7.10	14.4
Massey Ferguson 8200	9.46	9.14	3.8		2,120	200	7.40	13.3
Average value:	**28.16**		**3.9**			**517**	**7.25**	
ClaasLexion 760 +	5.66	9.14	4.0	**3.5**	2,000	110	N/A	
ClaasCerio 930	4.68	9.14	4.5		2,000	92	N/A	
Average value:	**10.34**		**4.3**			**202**		
New Holland CR9.80 +	6.37	9.14	4.0	**3.3**	2,100	189.4	6.40	
New Holland 740CF30'DD	5.75	9.14	5.2		2,100	125	5.80	
Average value:	**12.12**		**4.6**			**314.4**	**6.10**	

A significant advantage of the John Deere S680i + John Deere 630f combine is obvious: the highest performance with the greatest speed, compared to other combine harvesters, combined with the lowest consumption of fuel and the best productivity. It should be noted that the price of the John Deere S680i is the highest of the samples presented.

It should be noted that the lowest productivity, 42% less than John Deere S680i + John Deere 630f, was demonstrated by the New Holland CR9.80 + New Holland 740CF30'DD combine. The yields harvested by the New Holland CR9.80 + New Holland 740CF30'DD were on average 15% lower than those of the John Deere S680i + John Deere 630f combine and its price is slightly lower than that of John Deere S680i.

The results of fuel consumption, according to chronographic data are listed in a Table 4.

Table 4. Fuel Consumption Results According to Chronographic Data

Combine Harvester + Reaper	Speed, km h^{-1}	Cultivated area, hectares	Rotations of the engine, RPM	Quantity of used fuel, L	Fuel consumption, L ha^{-1}	Productivity, kg h^{-1}
Massey Ferguson MF T7 +	4.0	18.70	2,120	317	16.95	7.10
Massey Ferguson 8200	3.8	9.46	2,120	200	21.14	7.40
Average value:	3.9	28.16			**19.05**	7.25
Claas Lexion 760 +	4.0	5.66	2,000	110	19.43	N/A
Claas Cerio 930	4.5	4.68	2,000	92	19.66	N/A
Average value:	4.3	10.34			**19.55**	
John Deere S680i +	5.2	17.15	2,050	319	18.60	7.07
John Deere 630f	5.0	9.29	2,050	191	20.56	7.36
Average value:	5.1	26.44			**19.58**	7.22
CASE IH Axil Flow 8230 +	3.5	16.77	1,950	369	22.0	6.90
CASE IH 3020 Flex	4.0	9.41	1,950	235	24.97	7.20
Average value:	3.8	26.18		604	**23.49**	7.05
CASE IH Axil Flow 8230 +	3.5	5.95	2,100	124	20.84	5.30
CASE IH 3020 Flex	4.0	4.72	2,100	104	22.03	7.20
Average value:	3.80	10.67		228	**21.44**	6.25
New Holland CR9.80 +	4.0	6.37	2,100	189.4	29.73	6.40
New Holland 740CF30'DD	5.2	5.75	2,100	125	21.74	5.80
Average value:	4.6	12.12		314.4	**25.74**	6.10

According to the data obtained, the Massey Ferguson MF T7 + Massey Ferguson 8200 combine showed the best results. It consumed the least amount of fuel, covered the biggest area, and gathered maximum amount of the harvest. According to the research results (Table 2), the Massey Ferguson MF T7 + Massey Ferguson 8200 combine performance was 35% lower comparing to the John Deere S680i + John Deere 630f. That significantly affects the length of the harvest. This is the result of the low speed and the capacity of the combine. At the same time it has a fairly low price.

Wheat quality is characterized by attributes related to the genetic traits, physiological performance and its physical state. These factors can be negatively impacted if the harvesting is delayed (Siddique & Wright, 2003). The use of combine harvesters in actual practice shows that nowadays harvesters do not deliver a high quality threshing. This is confirmed by the existing losses and high level of grain damage (Rozwadowski et al., 2018).

The results of detecting the adulterant content in a grain tank of a combine harvester are listed in a Table 5.

The speed of the machine, the density of the sowing and the cutting height determine the feed rate and affect the quality. The reel height and the rotational speed must allow the achievement of the efficient and smooth pushing of the crop into the header without causing shatter losses from affecting ears and stalks (Baerdemaeker & Saeys, 2013), however there are modern methods of the quality assurance collection today (Lenaerts et al., 2012). For example, Baerdemaeker & Saeys (2013) developed a multispectral sensor to measure the purity and quality of the harvested grain, or Lenaerts et al. (2012), who investigated the potential of LiDaR sensors for measuring the quality of the ejected straw. However, the sensors do not ensure high quality of measuring. Therefore, the analysis of the selected samples was conducted.

An indicator for assessing the quality of the threshing mechanisms of a combine harvester is determined by the amount of damaged seeds in the bunker, the quantity of grated grain and adulterants. The CASE IH Axil Flow 8230 + CASE IH 3020 Flex combine has the least amount of wastes in the bunker and the smallest amount of damaged seeds, with the largest grain adulterant volume and the highest grain yield. At the same time it has the lowest price. Analysing the quality of the threshing mill it was found that the Claas Lexion 760 + Claas Cerio 930 has a grain weight of 2.27 g, while the CASE IH Axil Flow 8230 + CASE IH 3020 Flex – 0.06 g; the grain adulterant volumes are 1.9 times larger, with 10% less underdeveloped seeds compared to the CASE IH Axil Flow 8230 + CASE IH 3020 Flex combine. All other indicators differ just slightly.

For loss results obtained after a passage of a combine, see a Table 6.

Due to a lack of accurate data about the yield condition on each of the individual investigated area, for the purposes of calculations we used an average value retrieved from the combine harvester on-board computers, thus, the average yield value is considered to be: 6,770 kg ha^{-1}. The smallest losses are 0.34% or 23 kg ha^{-1} produced by the New Holland CR9.80 + New Holland 740CF30'DD combine, the largest are 1.37% or 93 kg ha^{-1}– by the John Deere S680i + John Deere 630f combine.

Nowadays, a very small amount of organic fertilizers is applied in to the soil on the territory of Ukraine, which is considered to be disastrous (Melnyk et al., 2017). According to the research conducted by the Northeast Institute of Agriculture (Kornus, 2013), it is proved that even if all organic residues from the animal husbandry, including individual farming households, would be applied, the application standard will be only 0.6 t ha^{-1}. This digit is too low. Such a number of organic fertilizers can neither saturate the soil with necessary nutrients nor promote its structural transformation or impregnate it with biologically active organisms. As concluded in a study published by Stupak (2016), as well as in a study executed by Baumann et al. (2011), even though the soil erosion degradation has become a problem in a Soviet era already, it still remains a problem nowadays. Therefore, it is important to investigate the issue of the soil quality as well as the issue of leaving the plant residues in the field (NAAS, 2015).

Table 5. Results of Adulterants Detection in a Grain Tank of a Combine Harvester

Combine Harvester + Reaper	The sample record number	The weight of the sample, g	Mineral adulterant, g	Organic adulterant, g	Damaged seeds, g	Underdev d seeds, g
CASE IH Axil Flow 8230 +	1.1	100	0.02	0.42	0.20	1.66
CASE IH 3020 Flex	1.2	100	0.02	0.36	0.28	0.80
	1.3	100	0.08	0.42	0.30	0.92
Average value:			0.12	1.20	**0.26**	3.38
Massey Ferguson MF T7 +	2.1	100	0.02	0.26	0.28	0.20
Massey Ferguson 8200	2.2	100	0.02	1.08	0.34	0.30
	2.3	100	0.02	0.38	0.26	0.90
Average value:			0.06	1.72	**0.29**	1.40
John Deere S680i +	3.1	100	0.02	0.44	0.54	0.52
John Deere 630f	3.2	100	0.02	0.34	0.24	0.86
	3.3	100	0.02	1.26	0.42	0.64
Average value:			0.06	2.04	**0.40**	2.02
New Holland CR9.80 +	4.1	100	0.08	0.02	1.28	0.56
New Holland 740CF30'DD	4.2	100	0.06	0.02	0.96	0.80
Average value:			0.14	0.04	**1.12**	1.36
Claas Lexion 760 +	5.1	100	0.08	0.04	1.74	0.94
Claas Cerio 930	5.2	100	0.02	0.04	2.80	2.80
Average value:			0.10	0.08	**2.27**	3.74
CASE IH Axil Flow 8230 +	6.1	100	0.04	0.04	0.10	0.80
CASE IH 3020 Flex	6.2	100	0.02	0.04	0.02	3.36
Average value:			0.06	0.08	**0.06**	4.16

Table 6. Loss Results Obtained After a Passage of a Combine Harvester

Combine Harvester + Reaper	The area of the land, hectares	The number of studied areas	Productivity of a sample plot, kg ha^{-1}	The weight of the grains (on an area of 1 m^2)	Loss, kg ha^{-1}	Loss, %
CASE IH Axil Flow 8230 + CASE IH 3020 Flex	17.3	1.1	6,770	6.00	60.00	0.89
	17.3	1.2	6,770	3.30	33.00	0.49
	9.3	1.3	6,770	4.30	43.00	0.64
	The average by the areas of:			4.53	45.33	**0.67**
Ferguson MF T7 + Massey Ferguson 8200	17.3	2.1	6,770	3.10	31.00	0.46
	17.3	2.2	6,770	5.30	53.00	0.78
	9.3	2.3	6,770	6.20	62.00	0.92
	The average by the areas of:			4.87	48.67	**0.72**
John Deere S680i + John Deere 630f	17.3	3.1	6,770	10.20	102.00	1.51
	17.3	3.2	6,770	8.20	82.00	1.21
	9.3	3.3	6,770	9.50	95.00	1.40
	The average by the areas of:			9.30	93.00	**1.37**
New Holland CR9.80 + New Holland 740CF30'DD	6.0	4.1	6,770	0.80	16.00	0.24
	5.0	4.2	6,770	1.50	30.00	0.44
	The average by the areas of:			1.15	23.00	**0.34**
Claas Lexion 760 + Claas Cerio 930	6.0	5.1	6,770	0.80	16.00	0.24
	5.0	5.2	6,770	6.40	128.00	1.89
	The average by the areas of:			3.60	72.00	**1.06**
CASE IH Axil Flow 8230 + CASE IH 3020 Flex	6.0	6.1	6,770	0.40	8.00	0.12
	5.0	6.2	6,770	3.70	74.00	1.09
	The average by the areas of:			2.05	41.00	**0.61**

Accordingly, the plant residues must be grinded and evenly distributed all over the surface of the soil. It was found that a rotary combine has a special technological process of threshing which allows it to smash the straw more intensely compared to a drum combine (Kumhála et al., 2005). This improves quality of the next cultivation, eliminates problems related to clogging of working parts of the combine, as well as provides an even saturation of the soil with organic fertilizers, which as a result allows to create the optimal conditions for the growth and development of the future crops. In addition, with the No-Till approach the even distribution of plant residues provides an elongation of the moisture in the soil (João et al., 2016).Therefore, the performance of a straw spreader was examined within the study of qualitative indicators of combine harvesters as well.

Grinding and Distribution of Crop Residues

In the course of studies of the work of combine harvesters, we measured the quality of the shredder. The results are presented in the Table 7.

Table 7. Grinding and Distribution of Crop Residues

Combine harvesters	Quality of the shredder combine harvester	
	Distribution of crop residues over the entire width of the reaper	Ejection of plant mass onto standing plants left along the edges of the passage
New Holland CR9.80 + New Holland 740CF-30'DD	+	+
ClaasLexion 760 + ClaasCerio 930	-	+
Case IH Axil Flow 8230 + Case IH 3020 Flex	+	+
Massey Ferguson MF T7 + Massey Ferguson 8200	-	±
John Deere S680i + John Deere 630f	+	+

The results of the study of the combine harvesterNewHollandCR9.80 with a reaper NewHolland740CF-30' DD demonstrated a good quality and equal distribution of crop residues over the entire width of the reaper. It was noted that no plant masses were thrown on the standing plants, left on the edges of the passage.

According to the results of the study of the combine harvesterClaasLexion760with a reaper ClaasCerio930, an uneven and incomplete distribution of crop residues on the working width of the reaper was noted. It was noted that no plant masses were thrown on the standing plants, left on the edges of the passage.

The results of the study of a combine harvesterCaseIHAxilFlow8230with a reaper CaseIH3020 Flex demonstrated a high quality and an equal distribution of crop residues along the entire width of the reaper. It was noted that no plant masses were thrown on the standing plants, left on the edges of the passage.

The results of the study of a combine harvesterCaseIHAxilFlow8230with a reaper CaseIH3020 Flex demonstrated a high-quality and an equal distribution of crop residues along the entire width of the reaper. It was noted that no plant masses were thrown on the standing plants, left on the edges of the passage.

On the Quality indicators of the grinder of a combine harvester is affected by:

- threshing system;
- design features of the structure of the chopper;
- quality settings of the chopper.

Modelling Operating Modes of the Combine Harvester with the Definition of its Operational and Qualitative Performance Indicators

Ismail et al. (2009) noted that the cost of harvesting makes up about 35% of the total crop production costs, and there is a need for development of reliable methods for selecting optimal machines for harvesting in specific natural areas. For the analysis in the chapter "Results and Discussion" only JohnDeereS680 + JohnDeere630f was chosen, because we managed to conduct more in-depth investigations only with this machine. Based on the results of the calculation, certain dependencies were noted:

- Productivity of a combine – on the width of the working grip (Fig. 4),
- Fuel consumption by a combine harvester – on the width of the working grip (Fig. 5),

– Productivity of a combine harvester – on the actual operating speed (Fig. 6),
– Fuel consumption – on the actual operating speed of a combine harvester (Fig. 7),
– The number of damaged seeds caused by the moving combine with an actual operating speed (Fig. 8),
– The number of losses caused by the combine moving with an actual operating speed (Fig. 9).

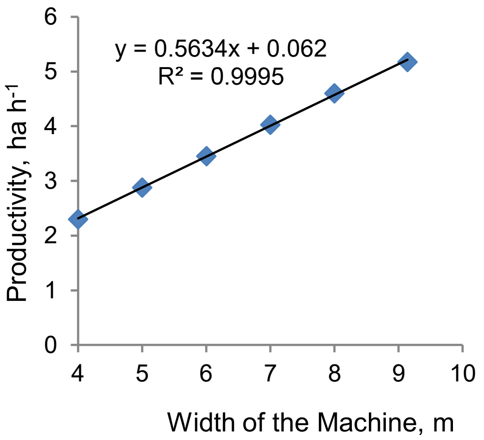

Figure 4. Dependence between the Work Productivity and the Working Width of the Grip of John Deere S680i with a John Deere 630f Reaper.

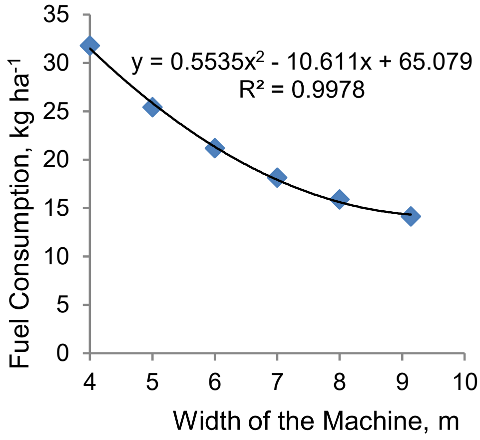

Figure 5. Dependence between the Work Fuel Consumption and the Working Width of the Grip of John DeereS680i with a John Deere 630f Reaper.

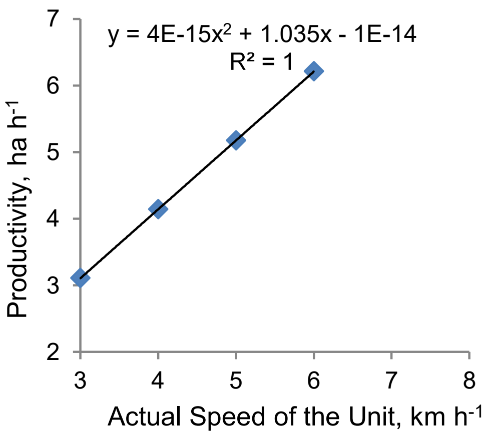

Figure 6. Dependence between Productivity and the Actual Operating Speed of the John Deere S680i Harvester with the John Deere 630f Reaper.

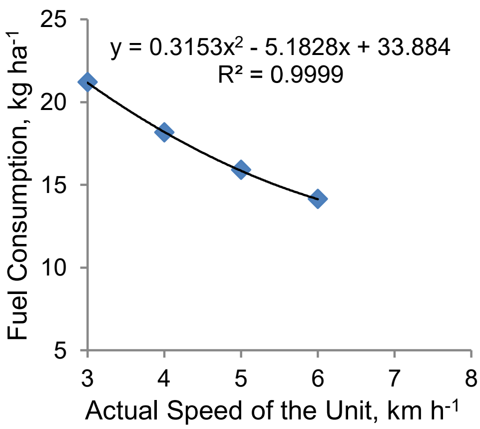

Figure 7. Dependence between Fuel Consumption and the Actual Operating Speed of the John Deere S680i Harvester with the John Deere 630f Reaper.

According to the analysis of the chart for work productivity dependence on the working width of the grip, it can be concluded that with the increase in the width of the grip, productivity performance of the machine increases as well.

To save the time and to guarantee the high productivity and quality of harvesting, it is desirable to predict their operating parameters using a mathematical model. The working parameters of the combine were analysed on the basis of the characteristics of the actual fieldwork and the mathematical model of losses. The reduction of the threshed grain quality was established in accordance with the classical empirical equations of rotary threshing.

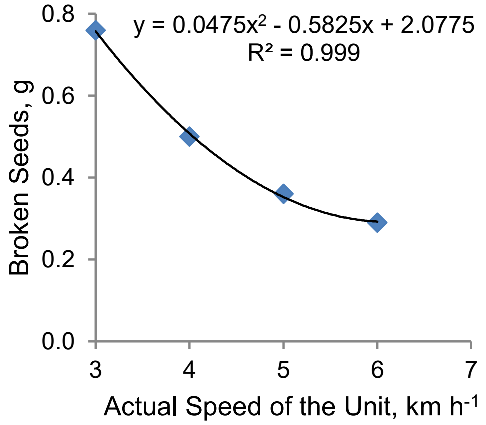

Figure 8. Dependence between the Quantity of Damaged Seeds and the Actual Operating

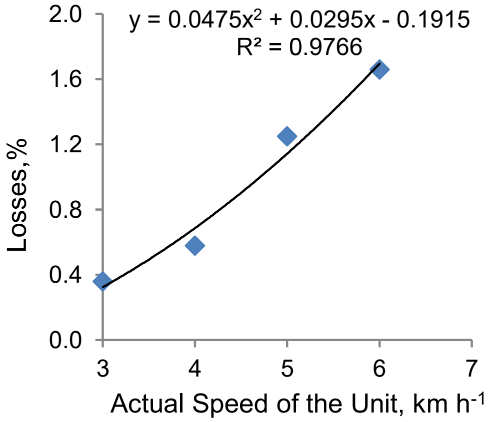

Figure 9. Dependence between the Volume of Losses and the Actual Operating Speed of the John Deere S680i Harvester with the John Deere 630f Reaper.

Upon analysing quantitative indicators, it was found that when using a constructive width of the grip of 9.1 m and a speed of 5 km h^{-1}, the productivity of a combine is 5.2 ha h^{-1}. However, when using a 4 m width of the grip, the productivity of combine harvesters drops by 56% to 2.3 hectares per hour. The change of the reaper width also significantly affects the fuel consumption. As such, using the JohnDeereS680icombine harvester with a JohnDeere630f reaper at an optimal 9 m reaper width results in the fuel consumption at the level of 14.1 kg ha^{-1}. In case the width of the reaper is reduced to 4 m, it leads to the overconsumption of fuel, which is 31.8 kg ha^{-1}, that is 57% higher than the norm.

The second experiment was focused on determining the dependencies between the productivity and the fuel consumption change during the change of the working speed of a combine with the constant width of the reapers.

Our results show that productivity of a combine harvester increases along with its working speed. This reflects a linear dependence between the parameters. As such, an increase in speed from 3 to 6 km h^{-1} resulted in an increase in productivity by 3.1 hectares per hour, meaning an increase in productivity by 49%.

Based on our results, it was found that a change in working speed of a harvester significantly affects its fuel consumption, particularly an increase in speed results in a decrease in cost per hectare. This happens due to a more effective method of the harvester loading. So, when the actual speed of the unit increases from 3 to 6 km h^{-1}, the fuel consumption decreases down to 7.07 kg ha^{-1} or by 33%.

According to the analysis conducted on the quality of work performed by a combine with different speed levels, it was determined that an increase in the actual speed of the unit from 3 to 6 km h^{-1} leads to a decrease in the number of damaged seeds by 0.47 g, meaning decrease of damaged seeds by 62%.

During the analysis of the quality of work performed by a combine harvester, it was found that an increase in the speed of the machine from 3 to 6 km h^{-1} led to an increase in a number of seeds lost by 1.3%.

Thus, to ensure the effective operations of enterprises, the management has to choose an effective combine harvester for their business purposes in accordance with their main requirements. In addition, the enterprise needs to be provided with an additional tool for analysing technical and economic indicators of the equipment operation. This will optimize technical and economic indicators of the enterprise as well as the quality of the technological operations.

CONCLUSIONS

For the purposes of ensuring financial efficiency of the profitable farming system, it is necessary to select the fleet of machines that meets the requirements of the enterprise activities. For this sake, it is meaningful to conduct the analysis of the equipment with the use of the 'Machine Unit' software in order to determine optimal equipment for the existing operational conditions. At the second stage, technical and economic indicators as well as indicators of quality of the selected units under an actual production conditions must be determined.

During the research conducted in the Sumy region (Ukraine) that took place from July to August 2016 the following outcomes were obtained:

i) The volume of grain loss after the passage of a combine harvester on a 1 m^2 area was the least in case of the John Deere S680i + John Deere 630f use. It had the highest productivity and speed, and the lowest fuel consumption, compared to other combine harvesters;
ii) The Massey Ferguson MF T7 + Massey Ferguson 8200 had the lowest fuel consumption according to the chronographic data;
iii) CASE IH Axil Flow 8230 + IH CASE 3020 Flex had the lowest amount of adulterants in the grain tank and the smallest number of damaged seeds;
iv) New Holland CR 9.80 + New Holland 740CF30 ' DD had the lowest grain loss after the harvester passage;
v) New Holland CR9.80 + New Holland 740CF-30'DD, Case IH Axil Flow 8230 + Case IH 3020 Flex, John Deere S680i + John Deere 630f provided the even distribution of plant residues on the field surface and the absence of throwing the plant mass on the standing plants at the edges of the passage.

The John Deere S680i combine, used by the enterprise, had the least volume of grain loss after its passage on 1 m^2 area, however, it cedes to the other equipment in terms of the fuel consumption, presence of adulterants in the grain tank and the volume of grain loss caused by the passage of a harvester.

Basing on the results of the experiment, it was determined that the difference between the results of the theoretical estimation and the experimental research of technical and operational indicators is within 2.5–4%. Therefore, the estimation results match the practical ones.

The economic calculations of the process will help farmers to choose the optimal equipment for their actual needs and will assist in making management decisions.

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