

UDC: 633.11-021.465:631.24:656.073.23

## RESEARCH AND OPTIMISATION OF THE QUANTITATIVE AND QUALITATIVE CHARACTERISTICS OF GRAIN SHIPLoad LOTS IN GRAIN TERMINALS

DOI: <https://doi.org/10.15673/fst.v14i4.1899>

### Article history

Received 11.06.2020

Reviewed 23.07.2020

Revised 27.10.2020

Approved 08.12.2020

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### Cite as Vancouver style citation

Stankevych G., Kats A., Shpak V. Research and optimisation of the quantitative and qualitative characteristics of grain shipload lots in grain terminals. Food science and technology. 2020;14(4):130-139. DOI: <https://doi.org/10.15673/fst.v14i4.1899>

### Цитування згідно ДСТУ 8302:2015

Stankevych G., Kats A., Shpak V. Research and optimisation of the quantitative and qualitative characteristics of grain shipload lots in grain terminals // Food science and technology. 2020. Vol. 14, Issue 4. P. 130-139 DOI: <https://doi.org/10.15673/fst.v14i4.1899>

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### Introduction. Formulation of the problem

Though the farming lands where grain legumes and oil crops are grown in Ukraine are constant in size and number, these cultures' productivity and gross yield can unfailingly be increased by improving the technologies of their cultivation. Today's high level of production of cereal crops and a number of external factors (Ukraine's joining the WTO, integration processes, market reorientation, etc.) result in larger volumes of grain exported to different countries by water. In recent years, grain terminals have been built intensively in Ukrainian ports. The main task of these terminals is to concentrate grain of different cultures and organise its export.

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**Abstract.** The structure of loading different crops onto vessels at the company *Ukrelevatorprom*'s grain terminal has been considered. The total grain shipped in 2012–2015 was comprised of 33.7–41.5% of maize, 19.7–32.2% of wheat, 14.4–26.0% of rapeseed, 6.7–14.2% of barley, and 5.4–11.0% of soya beans. When forming a 35,000-tonne grain shipload, grain lots stored in silos are sometimes of lower quality than contracts require: the protein and gluten contents can be inappropriate, or there can be smut grains or those damaged by sunn pests. The accepted technology of grain shipload formation does not guarantee that the grain quality will be uniform throughout the whole period of loading a vessel, especially in the beginning. In the first 1,000 tonnes of a grain shipload formed, the weight content of wet gluten was found to be 22.6% instead of 23%, the Falling Number was 145–180 s instead of 230s, and the content of smut grains was not the tolerable 5%, but 6.95–7.8%. The subsequent 2,000–3,000 tonnes of wheat, too, had the Falling Number lower than the contract prescribed (142–215 s), and only further on, its value achieved the required range 295–356 s. In the wheat sample formed from 5,000 tonnes, only the test values of the Falling Number (176s) and the content of smut grains (5.1%) were different from what the contract required. The calculated arithmetic means of the quality parameters of the 5,000-tonne wheat samples formed were practically the same as those determined experimentally, except for the values of the Falling Number and the smut grain content. The values of the coefficient of variation obtained showed that the grain lot was of non-uniform quality: it varied in such parameters as the foreign material (20.82–50.93%), sunn pest-damaged grains (7.41–25.76%), Falling Number (8.76–36.36%), and smut grain content (35.88–78.34%). Application of linear programming methods to optimise the shipload composition has allowed all the quality parameters to meet the contract requirements. Loading grain from all silos simultaneously, with the optimum flow ratio, will result in its even distribution in a shipload, and the grain lot will be of higher quality by all the parameters the contract specifies.

**Keywords:** grain terminals, wheat quality parameters, grain lot formation, coefficient of variation, optimisation of the grain lot composition.

Significant yearly oscillations of grain quality and the increased tonnage of vessels grain is exported on make forming grain shiploads quite a problem. This can cause a significant drop in their quality and non-compliance with the requirements of a contract. Studying and improving methods used to form grain shiploads of contracted quality are highly topical and important tasks.

### Analysis of recent research and publications

Ukraine is one of the main players in international grain markets. Exports from Ukraine make grain more available globally, thus contributing to food safety. Due to its farming

traditions, favourable agroclimatic conditions, and high-quality soil resources, the country can grow various cereal, leguminous, and oil crops. The most popular crop is wheat. The entire Ukrainian agribusiness is involved in its production, the volume of which makes 40–50% of all cereals [1,2].

The bumper crops in recent years have increased Ukraine's wheat export potential to over 20 million tonnes [3]. However, high crop yields are usually accompanied by their lower quality characteristics. To fulfil contracts, exporters have to reorient themselves towards new markets, collect grain from different regions to make up consignments to be shipped abroad, and often form them by mixing grain of different quality.

Currently, the Ukrainian Ministry of Agrarian Policy is working on adapting and harmonising the methods and standards of classifying grain and determining its quality, thus making them closer to the so called European standards. Until recently, there were a number of declarations that the very grain standards of Ukraine should be brought in line with the European ones. However, it appeared that the parameters of assessing grain quality in Ukraine were hardly commensurable with those used in other countries of the CIS, or North America, or the EU: so different these parameters were, and so differently treated. Indeed, very often, it is not the classification that matters, but the methods of determining the quality indicators to base this classification upon [4-6].

It is important to adapt the Ukrainian State Standards (DSTU) and quality assessment methods to their western equivalents. Even when comparing the formulations, one can see the differences in the very approaches: for example, the State Standard of Ukraine prescribes determining wet gluten in grain, and according to the international standards, it must be determined in wheat flour.

The EU standardisation system requires that protein should only be determined for durum wheats, while gluten is not supposed to be determined at all. However, in some countries (Austria, Hungary, Russia, Kazakhstan, and others), wheat is standardised according to its gluten content. In our country, the quality of wheat is still based on its gluten content (DSTU 3768-98), which is still determined by hand. International standards prescribe automated gluten washing using special equipment and a silk sieve, and handwashing is only allowed in certain cases. During this procedure, it is also controlled how efficiently the water is used [4,5,7,8].

As Ukrainian standards are imperfect and inconsistent with international requirements, there are disagreements between buyers and exporters. This should not, though, limit Ukraine in delivering its grain to other countries or result in any discrimination because of its non-conformity.

The US official standards for wheat are based on the commercial properties of grain: plumpness, kernel

hardness, soundness, colour, general condition, etc. The water content, protein level, and some other parameters are not considered determinative enough. The grain standards in the USA distinguish among six wheat types, mainly based on the sowing period, and besides, on the colour, vitreousness, and kernel hardness. These types include durum, hard red spring, hard red winter, soft red winter, hard white, and soft white. There are two extra types beyond these six categories: unclassified and mixed wheat [4,9].

In Europe, the content of protein or gluten is not a key factor to determine the quality of wheat. However, this is not so for high-quality milling wheat where the protein content determines the quality of finished products. The main characteristics used in the methods of assessing the grain quality are test weight, purity, and the external consumer properties: colour, smell, saleable condition, etc [4].

Grain from the EU is exported through official export trading exchanges. Unlike it is on the exchanges of Ukraine or the USA, here, the quality of grain offered for bidding is assessed according not to state standards, but to the demands of the exchange. These demands can be discrepant with conventional classifications. Nevertheless, the methods to determine the parameters of the quality of grain auctioned are strictly specified by national and global standards.

Therefore, when exporting grain from Ukraine, one should consider in advance the traditional (average) potential applications of the grain to be sold. The grain qualities should be compared not only by how much protein or gluten it contains: it is as important to collate the quality levels and other consumer properties of products of grain processing.

It is hardly possible to collate all the existing standards, because in different countries, classification parameters are determined by different methods. However, it is possible to certify samples of wheat which is classified according to the effective standards of certain countries. For example, those accepted in Ukraine can be compared with the American ones, and vice versa. When determining the quality parameters, it is important to use the same methods of analysis as buyers from abroad would use.

Besides, the price should be viewed as an indicator formed by market factors. In different years, grain with different quality characteristics can differ in price greatly. The same holds true for the difference in prices for the same commodity in different locations worldwide or even within Ukraine. Thus, with the market factors left out, it is solely up to the contracting parties to decide how the price will depend on the quality [4,10-12].

A possible way of improving the quality of grain lots is forming shiploads from different classes of grain and grading it by different characteristics. Grading can allow obtaining high-gluten grain flows. Usually, worse grain is admixed to better lots of grain already graded.

As a result, grain shiploads of mean quality are obtained, which helps increase the profit [13].

The quality parameters of grain that enters grain processing enterprises are unstable. They vary widely depending on the agroclimatic conditions of cultivation and varietal features. That is why grain to be milled is formed into milling blends, which allows more effectively using the grain materials present at an enterprise and stabilising both the course of grain processing and the quality of finished products. This is aimed at obtaining a grain lot of mean quality, which is further processed over quite a long period [14].

When forming milling blends, such parameters as gluten quality and Falling Number are calculated by the method of inverse proportions [15]. The Falling Number is also calculated by the graphical analytical method. Prior to applying it, the Liquefaction Number (LN) should be determined. Since the Falling Number value is logarithmically dependent on  $\alpha$ -amylase activity, it is impossible to calculate it in a milling blend: the expected value will always be higher than the real one [14].

Different crops have a great many grain quality parameters varying widely. That is why nowadays, to form export consignments of the contracted quality, grain stockpiling enterprises and grain transloading terminals use established methods of calculating and forming milling blends. However, grain delivery contracts include many more quality indicators than milling blends have. Besides, grain shiploads are so large (50,000 tonnes and more) that exporters have to use grain from quite a number of silos, which differ in the quality of the grain stored. This makes it difficult to balance the grain flows from different silos when forming shipload lots, and does not allow mixing the grain uniformly, let alone optimising the composition and quality of a consignment.

Regretfully, in literature, there are almost no studies of how to evaluate the uniformity of grain distribution when forming shipload lots and how to improve the methods of calculating and optimising them. These problems determined the purpose and the objectives of this research.

The **purpose of the research** is to study how the indicators of wheat grain quality change when grain lots are formed and loaded at grain terminals, which will allow improving their quantitative and qualitative characteristics.

The **objectives of the research** were:

- to analyse the structure of cereal crops loaded onto ships at a grain terminal;
- to study the quality parameters of wheat grain from different silos of an enterprise and the requirements that contracts imposed on shipload lots;
- to analyse the technology of forming consignments of grain at a grain terminal, and to study the dynamics of the change in their quantitative and qualitative characteristics in the grain mass;
- to determine the statistical characteristics and to study the uniformity of distribution of grain with

different quality parameters while forming a grain shipload lot;

- to optimise the composition of a grain shipload lot using linear programming methods, thus achieving its lowest cost and compliance with the quality requirements specified in the contract.

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### Research materials and methods

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The research was conducted in a production environment at the company *Ukrelevatorprom* in 2012–2019. The grain tested had been brought to the grain terminal from different regions of Ukraine.

At the first research stage, the data from weight reports were statistically analysed. Based on this, the quantitative and qualitative characteristics of grain harvested in 2012–2015 were determined: the crops, their volumes and ratios. At the second stage, in April 2019, while loading wheat grain harvested in 2018, the current experimental values were determined for the quality indicators the contract specified for the shipload lot formed. The data obtained were processed in order to determine the statistical characteristics of the shipload: the mean values, standard deviations, and coefficients of variation based on them. They allowed assessing the changes in the quality indicators under study and the uniformity of their distribution in the dynamic grain mass of a shipload lot. At the final research stage, it was shown how linear programming methods could be applied to calculate and optimise the composition of a grain shipload.

To characterise the grain quality, the following parameters were determined: water content, foreign material content, mass fraction of protein, mass fraction and quality of gluten, Falling Number, content of smut grains and of those damaged by sunn pest. The water and protein contents were determined by infrared spectroscopy on an analyser FOSS Infratech (DSTU 4117:2007), the content and quality of gluten by the mechanical technique on an analyser PertenGlutomatic (DSTU ISO 21415-2:2009), the Falling Number by the standard Perten-Hagberg method using a Perten Falling Number instrument (DSTU ISO 3093:2009), the test weight by the volume-weight method using a one-litre drop-weight grain tester (GOST 10840-2017, IDT), the foreign material content by means of sieve analysis, and the contents of smut grains and sunn pest-damaged grains were determined by visual estimation (GOST 30483-97, DSTU 3768:2010).

The uniformity of the quality of a shipload lot being formed was estimated as follows. While the ship was being loaded, samples were collected from every 500 tonnes of grain placed onto it, and the above parameters of their quality were determined. On loading 5,000 tonnes of wheat, one averaged sample was formed from the ten, and its quality was determined according to the parameters specified in the contract. Thus, each quality indicator of a 5,000-tonne shipload had 10 numerical values. These data were used to calculate the following characteristics of the grain lot: the mean value, the

standard deviation, and, based on these, the coefficient of variation. The value of the latter showed the level of non-uniformity of the grain lot resulting from the uneven distribution of each grain quality indicator in the shipload lot formed. These statistical characteristics were calculated in the MS Excel environment by the formulae:

$$\bar{Q}_j = \frac{\sum_{i=1}^n Q_{i,j}}{n}; S_j = \frac{\sum_{i=1}^n (Q_{i,j} - \bar{Q}_j)^2}{n-1}; V_j = \frac{100 \cdot S_j}{\bar{Q}_j}, \quad (1)$$

where  $\bar{Q}_j$  is the average value of a  $j$ -th quality indicator of a 5,000-tonne averaged grain sample;

$Q_{i,j}$  is a  $j$ -th quality indicator of an  $i$ -th grain sample weighing 500 tonnes;

$n$  is the number of grain samples ( $n=10$ );

$S_j$  is the standard deviation of a  $j$ -th indicator of the grain quality;

$V_j$  is the coefficient of variation of a  $j$ -th indicator of the grain quality.

For a shipload lot formed from individual grain lots of certain quality (specified by the contract's quality requirements for wheat) that had been stored in separate silos, the optimum composition was calculated by linear programming methods. In particular, the *Solver* procedure of the MS Excel spreadsheet was used.

### Results of the research and their discussion

The first research stage was devoted to analysing the quantitative and qualitative characteristics of the composition of grain and oilseeds loaded onto vessels at *Ukrelevatorprom* in 2012–2015. The results are presented as a histogram (Fig. 1) showing the proportions of different crops in the total volumes of grain loaded onto ships in different years.

One can see that throughout the whole period considered, the highest proportions were those of maize. In 2013, its volume loaded was the largest – 41.5%. In 2012, 2014, and 2015, the proportions of loaded maize were a little lower and ranged slightly within 33.7–36.0%.

The next highest proportions of the crops loaded by the company were those of wheat grain and rapeseed. The proportions of wheat loaded in 2012–2015 varied within 19.7–32.2%, the peak was registered in 2012, and in the following years, they decreased to 19.7–24.0%. The volumes of loaded rapeseed were within 14.4–26.0%, with the peak in 2013.

The last two crops loaded in the similarly little proportions 6.7–14.2% and 5.4–11.0% were, respectively, barley grain and soya seed.

To form shiploads of wheat (one of the main cereal crops), it is received by an enterprise and stockpiled in separate silos. Up to the year 2019, it was stored according to classes 1 to 6 (DSTU 3768-2010). Now, by the new standard, it is sorted into classes 1 to 4 for storage (DSTU 3768:2019). There can also be some substandard wheat. As wheat grain differs in quality, the ratio of its

classes usually changes with years. In 2013–2014, most wheat grain was of classes 2–3 (37–48%) and 5–6 (3–10%), but there was almost no grain of classes 1 and 4.

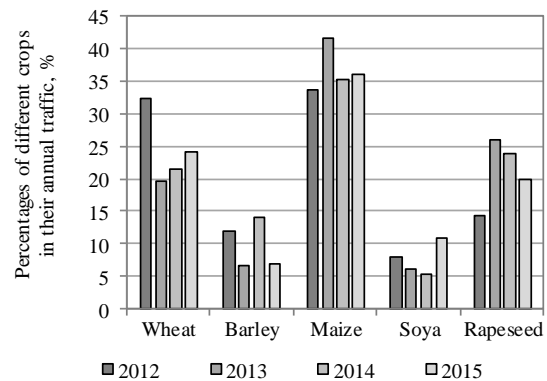


Fig. 1. Percentages of different crops in the annual volumes of grain loaded onto vessels in 2012-2015

At the next stage, a real industrial process of formation of a wheat grain shipload lot was studied. The company *Ukrelevatorprom* uses the following shipload-forming technology. First, the contract's requirements to the quality parameters of a grain lot are analysed. Then silos are selected where most parameters are the same as those required by the contract. The critical indicators, with values different from the ones specified in the contract, are isolated. A sufficient number of silos should be chosen to provide the required volume of grain for the shipload lot to be formed.

The calculated proportion (percentage) of nonstandard wheat added to food-graded wheat before loading a vessel is based on the quality parameters specified in the export contract and on the averaged quality parameters for each silo, which are taken from the report *IC:Accounting*. When doing the calculation, it is important that the worst averaged quality indicator of the silos, during mixing, should not exceed the corresponding parameter in the contract. In the course of loading a vessel, the laboratory controls the actual quality and corrects the proportions.

The equipment available allows loading grain onto a vessel from the silos located in Sector 1 using one conveyor with the capacity 500 tonnes/hour, and from Sector 2, using three conveyors, 600 tonnes/hour each. The total productivity of the line loading grain onto vessels is 1200 tonnes/hour.

Let us consider in detail the formation of a shipload lot in *Ukrelevatorprom* when loading wheat grain onto a vessel with the displacement tonnage 35,000 in April 2019. Table 1 presents the quality parameters of wheat grain stored in the silos chosen to load the vessel from. The silos are located in two production sectors of the enterprise. Besides, the table contains the standardised values of class-determining grain quality parameters for each class of wheat (DSTU 3768-2010. Wheat. Specifications) and the requirements of the contract to a shipload lot.

Table 1 – Quality indicators of wheat harvested in 2018, stored in silos, and intended for shipload lot formation; requirements to the wheat grain classes according to DSTU 3768-2010 and to the contract (n=3, p=0.95)

Number of the silo and the sector	Wheat class	Class-determining grain quality parameters									Not class-determining
		Water content, %	Test weight, g/l	Foreign material, %	Grain material, %	Mass fraction of protein, %	Wet gluten		Falling Number, s	Smut grain, %	Sunn pest-damaged grains, %
							Mass fraction, %	Quality, units of the GDM**			
<i>w</i>	<i>TW</i>	<i>FM</i>	<i>GM</i>	<i>P</i>	<i>MG</i>	<i>QG</i>	<i>FN</i>	<i>SG</i>	<i>SPG</i>		
2-1	3	12.2	799	0.7	5.5	12.0	23	75	315	<b>5.8</b>	1.2
7-1	nonst.*	12.9	795	1.3	6.3	12.0	24	78	296	<b>22</b>	<b>2.4</b>
11-1	3	12.3	793	0.6	5.5	11.6	24	90	301	5.0	0.8
18-1	2	12.7	801	1.1	5.8	13.0	28	80	339	3.0	1.5
21-1	5	12.0	785	0.7	5.8	<b>10.8</b>	<b>19</b>	91	320	3.0	0.9
23-1	2	12.6	800	1.0	6.1	12.7	27	78	313	3.2	1.1
1-2	6	12.0	790	0.7	6.8	<b>10.0</b>	<b>18</b>	85	250	<b>8.2</b>	1.4
7-2	3	12.1	791	0.8	4.1	11.8	23	89	386	3.8	0.9
9-2	3	12.2	795	0.7	5.2	11.7	<b>22</b>	85	350	4.2	1.0
Standards of quality parameters for each class											
	2	≤14.0	≥740	≤2	≤8	≥12.5	≥23	45–100	≥180	5	
	3	≤14.0	≥730	≤2	≤8	≥11.0	≥18	20–100	≥150	8	
	4	≤14.0	≥710	≤2	≤10	≥12.5	–	–	≥150	5	
	5	≤14.0	≥690	≤2	≤12	≥10.5	–	–	≥130	8	
	6	≤14.0	–	≤2	≤15	–	–	–	–	10	
	nonst.*	The wheat quality tolerance limit meets no parameter of the minimum quality standards of class 6 for common wheat; non-conformance is indicated (DSTU 3768:2010, paragraph 4.7).									
Contract requirements		≤13	≥770	≤2	–	≥11.5	≥23	–	≥230	≤5	≤2

Notes: \*nonst. – nonstandard wheat grain; \*\*GDM – gluten deformation meter.

Analysis of these data has allowed establishing the critical indicators of grain quality for each silo (highlighted in bold). For silos 2-1 and 7-1, it is the increased level of smut grains, for 21-1, it is the protein and wet gluten levels lower than it is required by the contract, for 1-2, it is not enough protein and wet gluten and an increased smut grain content, and for silo 9-2, the critical parameter is a slightly lower wet gluten level. In the indices of the silos, the first figure is the ordinal number of a silo, and the second indicates the production sector the silo is located in.

Thus, when feeding grain into a vessel's holds, the wheat from the above-mentioned silos with some critical quality parameters should be graded up by adding certain proportions of high-quality grain. While doing so, one should only control the actual values (test values) of the critical indicators of grain quality, as long as other parameters of the grain in silos comply with the contract requirements. Samples of grain, while it is transferred to a vessel, are collected at certain time intervals. These intermediate samples are tested to control their conformity with the contracted quality parameters. It looks more practical, though, to take samples after loading equal grain portions. At the enterprise, each 500<sup>th</sup> tonne of grain fed into the holds was sampled. Besides, out of these test portions, samples are formed for every 5,000 tonnes of the grain loaded, for each particular hold, and for the vessel in general. The samples are sealed by a surveyor

(independent inspector), who monitors the loading process.

The actual and averaged values were obtained experimentally for the quality parameters of the first 5,000 tonnes of wheat grain loaded in late April 2019 onto a vessel with the deadweight 35,000 tonnes. The grain started being loaded from Sector 1 (silos 7-1 and 21-1) and Sector 2 (silo 9-2). On emptying silo 7-1, the loading went on from silo 2-1. It should be emphasised that silo 7-1 contained large amounts of smut grain and sunn pest-damaged grain (22% and 2.4% respectively). The values obtained have been analysed, and the results are shown in Table 2.

Analysis of this table shows that at the very start of loading, some quality parameters of 500-tonne grain lots are below the contract requirements (highlighted in bold). Thus, in the first 1,000 tonnes of grain, the mass fraction of wet gluten was somewhat smaller – 22.6% instead of 23%, and the Falling Number, too, was 145–180 s instead of 230, whereas the smut grain content was 6.95–7.8%, which is higher than the normal value up to 5%. The loaded 3,000-tonne grain mass had the Falling Number smaller than that required by the contract. It varied within 142–215 s, and only with further loading, its values achieved the range specified in the contract (295–356 s).

Table 2 – Results of analysing the experimentally determined actual values of the quality parameters of wheat grain that was loaded from several silos in parallel ( $n=3$ ,  $p=0.95$ )

Weight of the grain loaded, t	Indices of the silos the grain was loaded from	Water content, %	Test weight, g/l	Foreign material, %	Mass fraction of protein, %	Mass fraction of wet gluten, %	Falling Number, s	Smut grain, %	Sunn pest-damaged grains, %
		<i>w</i>	<i>TW</i>	<i>FM</i>	<i>P</i>	<i>MG</i>	<i>FN</i>	<i>SG</i>	<i>SPG</i>
500	21-1, 7-1, 9-2	11.9	784	0.54	12.4	–	<b>180</b>	<b>7.80</b>	0.8
1,000	21-1, 7-1, 9-2	12.0	798	0.44	11.5	<b>22.6</b>	<b>145</b>	<b>6.95</b>	0.9
1,500	21-1, 7-1, 9-2	11.8	789	0.54	11.8	–	<b>190</b>	<b>13.10</b>	0.9
2,000	21-1, 7-1, 9-2	11.9	793	0.38	12.0	23.3	<b>142</b>	<b>9.70</b>	0.8
2,500	21-1, 7-1, 9-2	11.7	784	0.46	11.9	–	<b>158</b>	4.60	0.9
3,000	21-1, 7-1, 2-1, 9-2	11.7	798	0.34	11.6	24.3	<b>215</b>	3.00	1.0
3,500	21-1, 2-1, 9-2	11.7	804	0.34	11.6	–	343	1.40	0.9
4,000	21-1, 2-1, 9-2	11.8	795	0.30	11.7	23.0	356	2.25	0.9
4,500	21-1, 2-1, 9-2	11.9	800	0.40	11.8	–	321	1.60	1.0
5,000	21-1, 2-1, 9-2	11.9	794	0.34	11.6	24.4	295	1.40	0.9
Averaged sample	21-1, 7-1, 2-1, 9-2	11.8	798	0.49	11.7	23.8	<b>176</b>	<b>5.1</b>	1.0
Contract requirements		≤13	≥770	≤2	≥11.5	≥23	≥230	≤5	≤2

It should be pointed out that the 5,000-tonne averaged grain sample composed of the amounts collected for analysis has some quality parameters that do not meet the contract. These are the low Falling Number (176s) and the smut grain content somewhat higher than the norm (5.1%). Other quality parameters, though, comply with the contract requirements.

It has been noted that the samples to be tested in order to determine the actual quality parameters were collected from every 500 tonnes of the grain loaded. Thus, on loading 5,000 tonnes of grain, there were 10 grain samples available. They were used to form an averaged sample representing this volume of the grain loaded. The quality parameters of this sample, which were determined in the tests, gave an idea of the mean quality of the 5,000-tonne wheat grain mixture.

This mixture was tested for uniformity, because it included grain taken from several silos and simultaneously fed onto a conveyor and, further, into the holds. To this end, such a statistical characteristic as the coefficient of variation was used. It was calculated for each quality parameter according to the procedure described above.

The statistical values obtained are given in Table 3. Besides, it contains the experimentally determined parameters of the quality of the average grain samples weighing 5000 tonnes each.

Analysis of the data obtained has shown that the pre-calculated arithmetic mean values of the quality parameters of the 5,000-tonne grain mass loaded were practically the same as the ones determined by the tests (except for the Falling Number and the content of smut grains).

The calculated coefficients of variation allow estimating whether a wheat grain shipload formed is

uniform or not. There is a convention in statistics [16] that if the value of the coefficient of variation is lower than 33%, the mixture is considered uniform, if higher, non-uniform. That is, the 5,000-tonne wheat grain lot loaded at the beginning can be viewed as uniform by all of its quality parameters except for the Falling Number and, most notably, the content of smut grains. For the former, the coefficient of variation is 36.4%, and for the latter, it is 78.3%, which exceeds the permissible level by 33%.

However, from Table 3, it is clear that the arithmetic mean values of the same quality parameters are within the margin of error and thus meet the contract requirements. In the arithmetic means and the experimentally found quality parameters, the biggest relative errors are observed for the foreign material (16.3%), sunn pest-damaged grains (10.0%), and the Falling Number (32.9%). For the rest of the quality parameters, the relative errors are within 0.25–1.57%, which indicates splendid agreement between the arithmetic means and experimentally obtained values.

Analysis of entire Table 3 reveals that the least uniformity (the highest coefficients of variation) results from such parameters as foreign material (20.82–50.93%), sunn pest-damaged grains (7.41–25.76%), Falling Number (8.76–36.36%), and smut grain content (35.88–78.34%). Despite the high non-uniformity by these parameters, their numerical values are within the limits specified in the contract (the few exceptions have been indicated above). Nevertheless, as early as at the stage of determining the flows of grain loaded from certain silos, one should bear in mind a possibility of a shipload's low uniformity by the above parameters.

Table 3 – Experimental and statistical characteristics of the quality parameters of a 35,000-tonne shipload lot of wheat grain tested while loaded at a grain terminal

Weight of the grain loaded, t	Characteristics	Water content, %	Test weight, g/l	Foreign material, %	Mass fraction of protein, %	Mass fraction of wet gluten, %	Falling Number, s	Smut grain, %	Sunn pest-damaged grains, %
		<i>w</i>	<i>TW</i>	<i>FM</i>	<i>P</i>	<i>MG</i>	<i>FN</i>	<i>SG</i>	<i>SPG</i>
5,000	Experimental average	11.8	798	0.49	11.7	23.8	176	5.1	1.0
	Arithmetic mean	11.83	794	0.41	11.79	23.52	234	5.18	0.90
	Coefficient of variation, %	0.90	0.83	20.82	2.24	3.39	36.36	78.34	7.41
10,000	Experimental average	12.0	798	0.30	11.6	23.9	263	1.40	0.9
	Arithmetic mean	12.07	792	0.31	11.59	23.13	273	2.33	0.87
	Coefficient of variation, %	1.18	0.40	30.61	1.00	3.40	17.95	52.85	13.10
15,000	Experimental average	12.2	788	0.50	11.7	23.7	228	3.45	1.0
	Arithmetic mean	10.86	713	0.71	10.61	24.08	228	1.62	1.01
	Coefficient of variation, %	0.85	0.66	35.75	2.26	4.10	23.85	53.85	25.76
20,000	Experimental average	12.1	798	0.64	11.8	23.3	243	2.00	1.4
	Arithmetic mean	12.32	792	0.62	12.02	24.64	240	1.60	0.81
	Coefficient of variation, %	1.00	1.19	35.01	2.10	3.68	21.73	36.44	25.00
25,000	Experimental average	12.3	798	0.47	12.3	25.0	271	2.55	0.6
	Arithmetic mean	12.28	799	0.47	12.42	25.38	295	1.48	0.61
	Coefficient of variation, %	1.99	0.60	50.93	1.85	4.23	8.76	35.88	9.31
30,000	Experimental average	12.3	802	0.68	12.3	25.7	300	1.10	0.6
	Arithmetic mean	12.13	801	0.43	12.62	25.28	293	1.59	0.68
	Coefficient of variation, %	1.56	0.60	23.46	3.05	1.71	13.66	68.18	23.81
35,000	Experimental average	12.1	805	0.37	12.6	25.0	288	3.00	0.8
	Arithmetic mean	12.13	801	0.43	12.62	25.28	293	1.59	0.68
	Coefficient of variation, %	1.56	0.60	23.46	3.05	1.71	13.66	68.18	23.81
	Contract requirements	≤13	≥770	≤2	≥11.5	≥23	≥230	≤5	≤2

The research conducted has shown that to form a shipload lot, grain was simultaneously loaded from 2-6 silos, though it is technically feasible to load it from all the 9 silos in parallel. For this, though, one has to know the ratio of the volumes of grain loaded from each silo. There were 4 critical parameters indicating low uniformity of distribution in the grain mass, as shown above. This means that calculating the ratio of grain flows is hardly possible by the traditional methods typically used, for example, when forming milling blends at flour milling plants [14,15]. This is because these calculations involve but few parameters of grain quality and few individual lots of grain stored in different silos. However, when we form large shiploads from many silos, with numerous grain quality parameters (usually about a dozen), it is quite a task to determine the ratios among individual small-volume grain lots of different quality. It is not even about how to calculate the optimum composition of a lot like this – the challenge consists in how to meet the contract’s requirements to the quality of the lot formed.

Linear programming methods have been used to solve the problem of how to make the composition of a grain lot meet the contract requirements to grain quality, with the available grain stocks of certain quality taken into account. These methods, based on mathematical models of shipload lots and on requirements of a contract, allow finding all the necessary ratios among individual lots (silos) meeting all the quality requirements. Moreover, these methods make it possible to gain certain benefits, like the minimum cost of a consignment formed, or expending high-quality grain more economically, etc.

Table 4 – Volumes and prices of wheat grain in the silos (2018)

Number of the silo and the sector	Weight of grain in a silo $M_{i-j}$ , t	Price of grain, UAH/t
2-1	5800.14	5450
7-1	4156.15	5350
11-1	5314.60	5450
18-1	4858.96	5600
21-1	3430.94	5350
23-1	3712.92	5650
1-2	2810.25	5350
7-2	2885.98	5450
9-2	4763.44	5450

The composition of a shipload lot is calculated as follows. First, a so called objective function (or an optimality criterion) is formulated. Its value will show the calculation objective achieved. The objective function most common in solving compositional problems is the cost function. It means that calculation results in determining the cheapest grain lot of the quality conforming to the terms of the contract. The contract requirements are included in a mathematical model as *constraints* (a range of required values of each quality parameter specified by the contract).

We shall demonstrate the principle of calculating the ratios of grain flows at an enterprise. Our calculation will be based on the above-listed quality parameters of grain in different silos and on the contract requirements (see Table 1). For more accurate calculation, one should also know the grain volumes in each silo and prices of wheat grain (Table 4).

Let us develop a mathematical model of a shipload lot of grain. The objective function selected (*OF*) will be the cost of a grain lot to be formed. A grain lot of the optimal composition should have the minimum cost:

$$OF = 5450x_{2-1} + 5350x_{7-1} + 5450x_{11-1} + 5600x_{18-1} + 5350x_{21-2} + 5650x_{23-1} + 5350x_{1-2} + 5450x_{7-2} + 5450x_{9-2} \rightarrow \min, \quad (2)$$

where  $x_{i-j}$  is the percentage of grain from the *i*-th silo of the *j*-th sector in the newly-formed shipload lot of wheat, %.

Then the contract requirements to the quality parameters of the shipload lot are written down as constraints (inequalities).

The water content in grain should not be higher than 13.0%:

$$w = 12.2x_{2-1} + 12.9x_{7-1} + 12.3x_{11-1} + 12.7x_{18-1} + 12.0x_{21-2} + 12.6x_{23-1} + 12.0x_{1-2} + 12.1x_{7-2} + 12.2x_{9-2} \leq 13.0. \quad (3)$$

The test weight of grain should not be less than 770g/l:

$$TW = 799x_{2-1} + 795x_{7-1} + 793x_{11-1} + 801x_{18-1} + 785x_{21-2} + 800x_{23-1} + 790x_{1-2} + 791x_{7-2} + 795x_{9-2} \geq 770. \quad (4)$$

The foreign material content should not exceed 2.0%:

$$FM = 0.7x_{2-1} + 1.3x_{7-1} + 0.6x_{11-1} + 1.1x_{18-1} + 0.7x_{21-2} + 1.0x_{23-1} + 0.7x_{1-2} + 0.8x_{7-2} + 0.7x_{9-2} \leq 2.0. \quad (5)$$

The mass fraction of protein should not be less than 11.5%:

$$P = 12.0x_{2-1} + 12.0x_{7-1} + 11.6x_{11-1} + 13.0x_{18-1} + 10.8x_{21-2} + 12.7x_{23-1} + 10.0x_{1-2} + 11.8x_{7-2} + 11.7x_{9-2} \geq 13.0. \quad (6)$$

The mass fraction of gluten (not less than 23%):

$$MG = 23x_{2-1} + 24x_{7-1} + 24x_{11-1} + 28x_{18-1} + 19x_{21-2} + 27x_{23-1} + 18x_{1-2} + 23x_{7-2} + 22.0x_{9-2} \geq 23.0. \quad (7)$$

The Falling Number (not less than 230s):

$$FN = 315x_{2-1} + 296x_{7-1} + 301x_{11-1} + 339x_{18-1} + 320x_{21-2} + 313x_{23-1} + 250x_{1-2} + 386x_{7-2} + 350x_{9-2} \geq 230. \quad (8)$$

Smut grains (not more than 5%):

$$SG = 5.8x_{2-1} + 22x_{7-1} + 5x_{11-1} + 3x_{18-1} + 3x_{21-2} + 3.2x_{23-1} + 8.2x_{1-2} + 1x_{7-2} + 4.2x_{9-2} \leq 5.0. \quad (9)$$

Grains damaged by the sunn pest (not more than 2.0%):

$$SPG = 1.2x_{2-1} + 2.4x_{7-1} + 0.8x_{11-1} + 1.5x_{18-1} + 0.9x_{21-2} + 1.1x_{23-1} + 1.4x_{1-2} + 0.9x_{7-2} + 1.0x_{9-2} \leq 2.0. \quad (10)$$

Since a shipload lot will be formed from grain stored in different amounts in 9 silos, this is reflected in the mathematical model as the following constraints:

$$m_{i-j} = 35,000x_{i-j} / 100 \leq M_{i-j}, \quad (11)$$

where  $m_{i-j}$  is the estimated weight of grain from the *i*-th silo of the *j*-th sector in the shipload lot composition, t; 35,000 is the total weight of the shipload lot, t;

$x_{i-j}$  is the estimated proportion of grain from the *i*-th silo of the *j*-th sector in the shipload lot composition, %;

$M_{i-j}$  is the weight of grain (stockpile) in the *i*-th silo of the *j*-th sector, t (see Table 4).

Thus, this system of equations and inequalities (2)...(11) supplemented by the constraint of non-negativity of the variables  $x_{i-j}$  and by the condition that their sum is equal to 100% is a mathematical model of a grain shipload lot. Its unknowns are the values of  $x_{i-j}$  – the percentage of grain to be taken from the *i*-th silos in the *j*-th sector for a 35,000-tonne shipload lot. This system was solved using the *Solver* add-in of the MS Excel spreadsheet. The results obtained are presented in Tables 5, 6.

As one can see, a shipload lot formed according to the calculations performed will have the minimum price possible, and will meet the contract by all the quality requirements.

Field testing of the research results. These statistical characteristics (how the values characterising differences in the grain quality were distributed when forming a wheat grain shipload) were obtained in a production environment at the company *Ukrelevatorprom*. This can be considered partial field testing of the research results: they were calculated based on experimentally found actual values of the quality parameters of grain in individual silos, in the spot samples collected from each 500 tonnes during loading, and in averaged samples of every 5,000 tonnes of grain. Of course, the optimum composition calculated for a shipload lot should be put to additional production testing. It can be tested in grain terminals interested in forming grain shiploads of the optimum composition and quality.

Table 5 – Optimum proportions and weights of grain to be taken from the selected silos for a shipload lot

Parameters	Indices of the silos and the sectors they are located in									Total
	2-1	7-1	11-1	18-1	21-2	23-1	1-2	7-2	9-2	
Grain proportions $x_{i-j}$ , %	16.57	4.07	15.18	13.88	9.80	10.61	8.03	8.25	13.61	100.00
Grain weights $m_{i-j}$ , t	5,800.14	1,422.77	5,314.60	4,858.96	3,430.94	3,712.92	2,810.25	2,885.98	4,763.44	35,000.00

Table 6 – Estimated optimum values of the quality parameters of the planned shipload lot of wheat grain

Parameters	w, %	TW, g/l	FM, %	P, %	MG, %	FN, s	SG, %	SPG, %	Price, UAH/t
Quality parameter	12.31	795	0.80	11.82	23.38	321	4.98	1.15	5,470.14
Contract requirements	≤13	≥770	≤2	≥11.5	≥23	≥230	≤5	≤2	–

### Conclusions

1. It has been established that in 2012–2015, in the *Ukrelevatorprom* grain terminal, the proportions of annual volumes of different crops loaded onto ships

were as follows: 33.7–41.5% of maize, 19.7–32.2% of wheat, 14.4–26.0% of rapeseed, 6.7–14.2% of barley, and 5.4–11.0% of soya beans. To form wheat grain lots uniform by their quality (by the wheat class composition), the enterprise needs more silos than for other crops.

2. It has been shown that in some silos, before forming a shipload lot, the quality indicators of wheat grain are sometimes different from those required by the contract. The discrepancy with the contract requirements most commonly reveals itself in the low content of protein and gluten, increased content of smut grains and, sometimes, of those damaged by the sunn pest.

3. The technology of forming wheat shiploads that is traditionally used in the grain terminal does not ensure the uniform quality of grain throughout the whole period of loading a vessel, especially at its initial stages. In the first 1,000 tonnes of a grain shipload formed, the weight content of wet gluten was found to be 22.6% instead of 23%, the Falling Number was 145–180 s instead of 230s, and the content of smut grains was not the tolerable 5%, but 6.95–7.8%. The subsequent 3,000 tonnes of grain loaded, too, had the Falling Number 142–215 s, which was lower than prescribed by the contract. Only further on, its value achieved the required range 295–356 s. It has also been shown that in an averaged 5,000-tonne wheat sample formed from other samples collected, the tests revealed some quality parameters different from what the contract required: the low Falling Number (176s) and the slightly increased smut grain content (5.1%). Other quality characteristics, though, complied with the contract.

4. While a shipload lot was being formed, its statistical characteristics were determined. They have shown that the calculated arithmetic means of the quality parameters of the 5,000-tonne wheat samples

formed were practically the same as those determined experimentally, except for the values of the Falling Number and the content of smut grains.

The values of the coefficients of variation have shown that the first 5,000 tonnes of the grain lot loaded were practically uniform by all the quality parameters, but the Falling Number and, most notably, the content of smut grains. For the former, the coefficient of variation was 36.4%, and for the latter, it was 78.3%, which exceeds the permissible uniformity level by 33%. The high non-uniformity by the coefficients of variation was due to such parameters as foreign material (20.82–50.93%), sunn pest-damaged grains (7.41–25.76%), Falling Number (8.76–36.36%), and smut grain content (35.88–78.34%). This means that after grain with some quality parameters different from the contract requirements is taken from the silos, it is distributed unevenly in a shipload lot. So, grain flows from the silos should be rearranged. However, despite some non-uniformity of a grain lot at the start of its formation, the average values of the contracted quality parameters were within the standard limits.

5. A mathematical model of a shipload lot, with linear programming methods used, allows optimising its composition and thus meeting the contract requirements in all the quality parameters. Loading grain from all silos simultaneously (in parallel flows), with the optimum flow ratio, will result in its even distribution in a shipload, and the grain lot will be of higher quality by all the parameters the contract specifies.

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## ДОСЛІДЖЕННЯ ТА ОПТИМІЗАЦІЯ КІЛЬКІСНО-ЯКІСНИХ ХАРАКТЕРИСТИК СУДНОВИХ ПАРТІЙ ЗЕРНА НА ЗЕРНОВИХ ТЕРМІНАЛАХ

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**Анотація.** Розглянуто структуру відвантаження на судна різних культур на зерновому терміналі ТОВ «Укрелеваторпром». У 2012–2015 рр. було відвантажено 33,7–41,5% кукурудзи, 19,7–32,2% пшениці, 14,4–26,0% ріпаку, 6,7–14,2% ячменю та 5,4–11,0% сої. При формуванні суднової партії зерна пшениці масою 35 тис. т окремі партії зерна в силосах не завжди співпадають за якістю з вимогами контрактів, насамперед за вмістом білка, клейковини, сажкових та пошкоджених клопом-черепашкою зерен. Реальна технологія формування суднових партій зерна не гарантує рівномірної його якості впродовж всього періоду завантаження судна, особливо на його початкових етапах. Встановлено, що перші 1000т сформованої партії пшениці мали 22,6% масової частки сирогої клітковини замість 23%, число падіння дорівнювало 145–180 с проти 230 с, вміст сажкового зерна 6,95–7,8% замість 5%. У наступних 2000–3000 т пшениці було меншим від контракту число падіння (142–215 с) і лише у подальшому його значення увійшло в необхідний діапазон 295–356 с. У сформованому з 5000т зразку пшениці експериментальне значення лише числа падіння (176 с) та вмісту сажкових зерен (5,1%) не задовольняли вимогам контракту. Розраховані середньоарифметичні значення показників якості сформованих зразків пшениці масою по 5000т, практично не відрізнялись від експериментально визначених, окрім числа падіння та вмісту сажкових зерен. Отримані значення коефіцієнтів варіації показали значну неоднорідність якості партії пшениці за смітцевою домішкою (20,82–50,93%), пошкодженими клопом-черепашкою зернами (7,41–25,76%), числом падіння (8,76–36,36%) та вмістом сажкових зерен (35,88–78,34%). Оптимізація складу суднової партії методами лінійного програмування дозволила досягти дотримання вимог контракту за всіма показниками якості. Одночасне відвантаження зерна з усіх силосів за оптимальним співвідношення потоків дозволить забезпечити його рівномірний розподіл у суднової партії та підвищити її якість за всіма контрактними показниками.

**Ключові слова:** зернові термінали, показники якості пшениці, формування партій зерна, коефіцієнт варіації, оптимізація складу зернових партій.

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