Quantitative Assessment and Forecasting of Control Risks in the Ore-Stream Quality Management System

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***Abstract*—The paper is aimed at organizational and technological optimization of the system of remote control of ore-stream quality according to technical and economic criteria. The ore-stream in the environment of digital transformation of the mining industry is seen as a system where one of the main functions of management is control. The key importance of the control function in ore-stream quality management becomes in ore quality assessment at the stage of ore material technological preparation, where the homogeneity of the ore massif in terms of the content of the useful component from heterogeneous deposits is formed. Such component in the paper is iron. System technological novelty, which is presented in the paper, consists in realization of constant remote control of ore material quality in the form of monitoring. Remote control is technically realized using unmanned vehicles with subsequent digital processing of information by on-board microprocessor technology and special mathematical and software. The iron content of the ore is estimated from the vertical vector of the magnetic field of the ore material. The implementation of such a concept envisaged the solution of the following tasks: development of a structural and functional model of ore-stream quality control; development of mathematical support for the digital system of data processing of ore material magnetic field measurement data, optimization of metrological indicators of the measuring complex of the control system. It is proposed to use control risks as criteria for quantitative assessment of the functional quality of the ore-stream quality management system. The empirical function of the relationship between the cost of magneto metric remote control of iron content and probable control risks is found. A 3D model of the dependence of the cost of magnetometric control of iron content as a function of accuracy and the value of standards of iron content in ore was built.**

***Keywords*—Ore-stream; system; model; technology; control; risks; probability; unmanned vehicles**

I. INTRODUCTION

The aim of the work is organizational and technological optimization of the system of remote control of ore-stream quality according to technical and economic criteria. The achievement of the goal is proposed to be solved by developing information and analytical support for the ore-stream quality control system. The proposed study addresses two contextualized scientific and practical challenges that bridge the gaps of known studies: development of a structural and technological model of remote ore quality control and formalization of the process of quantitative assessment of control risks and decision-making under conditions of parametric vagueness of control agents and statistical uncertainty of technological data. Moreover, it is extremely important to differentiate the risks by the degree of their impact on the socio-economic activity of the mining enterprise [1.4].

One of the working and dominant hypotheses proposed in this research relies on the paradigm that decision quality is a systemic convergence of heterogeneous technological agents, where the control system, which finalizes almost every managerial decision, plays a decisive role.

This paper focuses on the function of digital remote control of ore-stream quality. The structural and functional model of the system digital support of the control process contains the following system components: technical support; mathematical support, software, information support, metrological support, organizational and methodological support.

The paper deals with the technology of remote control of iron ore quality. Ore quality in this paper is assessed by the percentage of iron content in a ton of ore material. In real production practice, an ore massif of controlled material is distributed on a solid base in the form of a rectangular ore body of 100x900 m. in the open air. This massif is called an “ore yard”. Measurement of iron level in the ore material is carried out by magnetometers according to the controlled value of magnetic field strength with a technological step of 10 m. over the entire area of the “ore yard”. An estimate of ore material quality is traditionally the average value of magnetic field strength in point coordinates of measurement Y_{ij} over the entire ore mass area in the ore yard. Control and measurement operations are accompanied by control errors, which are called risks and are differentiated by their economic content into “producer risk” and “consumer risk”. Such differentiation of risk is essential, as these types of risk lead to different socio-economic consequences in practice. Currently, the need for risk assessment in any project and production activity is regulated by the ISO 2015 version of the standard, which has a special supplement - IEC 31010 “Risk Management”. The main difference between this addition to the standard and previous versions of ISO is that “risks are no longer implicit in the standard, risk assessment is now embedded in the management system and becomes an inherent feature of it”. The problem of quantitative assessment of these risks in practice is that there is no possibility of instrumental measurement of these risks or by the method of statistical processing, but only by formal mathematical and simulation tools.

Thus, the proposed approach solves the problem of qualimetric integrated assessment in the system of control and decision making in a complex system in the conditions of digital transformation of business processes of the mining industry. Qualimetric support of ore-stream is provided by technological tools, such as remoteness of control and measurement operations [11].

The organizational structure contains: literature review of formal methods and models of risk assessment in management and control systems; problem; research methods; theoretical research results; computer modeling; conclusions.

II. LITERATURE REVIEW OF FORMAL METHODS AND MODELS FOR RISK ASSESSMENT IN MANAGEMENT AND CONTROL SYSTEMS

In classical and modern management science, it is believed that the management system is based on four functions: organization, planning, motivation and control [1]. Control is present to varying degrees in all management functions, but is often identified as a separate organizational or technological system agent. The process of control by the organizational and technical system contains the following sequence of operations: measurement; comparison of the measured value with the norm; analysis of the result; decision making [2,3,4]. The main focus of these papers is on the quantification of control errors (control risks), which are functions of statistical properties and characteristics of the agents of the control system. Statistical properties are understood as distribution laws, and most of the works investigated three laws: the normal law of distribution of a random variable (Gauss's law), Weibull's law, and the equal probability law [5,6]. The papers investigated the influence of the shape of statistical laws of distribution of controlled parameters on probable errors (risks) of control. At the same time, all researches propose different initial constraints, hypotheses and statistical conditions. Initial constraints include their form, e.g.: lower constraint norm, when the controlled indicator must be above the limit $S>S_l$; upper constraint norm, when the controlled indicator must not exceed the value $S<S_u$; tolerance constraint $S_l<S<S_u$. At each constraint, compositions of distribution laws of the controlled parameter and measurement error were investigated.

Under the probability of undetected reject P_{ur} is considered the case when the true value of the controlled parameter is outside the permissible limits, and the control system registers this fact as the presence of the parameter in the permissible zone. And vice versa, when the controlled parameter is in the tolerance zone, and the control system registers this fact as a parameter out of the tolerance zone with probability P_{fr}. The hypothesis of distribution of the controlled parameter and measurement error according to the Gauss law has been investigated in known works [7].

Some of the papers investigate the hypothesis of distribution of the controlled parameter according to the Weibull law, and of the measurement error according to the Gauss law. Using the integral function of the Weibull law, the expressions for calculating the probabilities of false reject - $P_{fr,}$ and the probability of undetected reject - R_{ur} in the following form [7,8]:

$$P_{fr}=\sum_{i=1}^{k}\left(e^{--\frac{S_i^\beta}{\alpha}}-e^{-\frac{S_{i-1}^\beta}{\alpha}}\right)$$

$$\times\left[\frac{1}{\sigma_y\sqrt{2\pi}}\int_{S_l}^{S_i-3\sigma_y}e^{\frac{y^2}{2}}dy+\frac{1}{\sigma_y\sqrt{2\pi}}\int_{S_u}^{S_i+3\sigma_y}e^{-\frac{y^2}{2}}dy\right]$$

$$P_{ur}=\sum_{i=1}^{k}\left(e^{-\frac{s_i^\beta}{\alpha}}e^{-\frac{s_{i+1}^\beta}{\alpha}}\right)\frac{1}{\sigma_y\sqrt{2\pi}}\int_{S_l}^{S_i-3\sigma_y}e^{\frac{y^2}{2\sigma_y^2}}dy\ \times$$

$$\sum_{i=1}^{k}\left(e^{-\frac{s_i^\beta}{\alpha}}e^{-\frac{s_{i+1}^\beta}{\alpha}}\right)\frac{1}{\sigma_y\sqrt{2\pi}}\int_{S_u}^{S_i+3\sigma_y}e^{-\frac{y^2}{2\sigma_y^2}}dy\ , \qquad (1)$$

Analyzing the nature of risk in an environment of parametric fuzziness and data uncertainty showed that risk represents some virtual space or augmented reality phenomenon. According to current digital understandings, this virtual environment is part of a “meta-universe”. The “meta-universe”, as noted in publications, is “far from being a new term” [9]. The first concepts of the meta-universe had only fantastical outlines related to travelling beyond the galaxy. It represents something between the real and fictional worlds. Nowadays, the concept of “meta-universe” has started to acquire practical contours and penetrate into many spheres of life, such as: social networks, real estate sector, investments, working sphere, augmented reality, cryptocurrency world, online games, etc. The challenge is to “look at life beyond the boundaries of conventional understanding”, which ultimately offers and generates the “digital transformation” of the risk management process. Nowadays, risk is an integral part of human “digital” life and is present in virtual and real forms of being, largely determining the “quality of life” at all stages of the “life cycle” of an object [10].

III. THE PROBLEM

The main problem is to quantitatively assess ore quality under production conditions while minimizing technological costs. The research is carried out on the example of quality control of iron-containing ore material at the final stage of technological preparation of ore for smelting. At this stage, the tasks of estimating the percentage content of the useful component in the ore mass and building an optimal technological model that ensures minimum risks of ore quality control and subsequent economic losses are solved.

IV. RESEARCH METHODS

The research methodology is based on the system approach. In this interpretation, the system is considered as an integrated set of controlling digital agents of a multi-parameter technical and economic system. The key agent in quality management of the object under research - ore flow - is considered to be the process of control and risks regulated by IEC 31010 standard. For the optimal solution of the problem, formal methods of description of production and technological processes in the environment of digital transformation of management are used. The formalization of solved problems relies on the following mathematical tools: probabilistic and simulation models, fuzzy sets, agent-based approaches, expert evaluations. The software application developed in previous researches is used to conduct the computer experiment. Statistical data for modelling are used from the reporting documents of sectoral enterprises. Fisher's F-criterion and Student's t-criterion were used to examine the statistical material for homogeneity. Statistica 10 package was used to process the results of statistical research.

V. RESULTS OF THEORETICAL RESEARCHES

A. *Virtual Paradigm of Ore-Stream Quality Control in the Environment of Digital Transformation of Mining Economy*

To achieve the goal in the scope of the proposed research the following tasks are solved: development of organizational and technological model of remote control of ore mass quality; optimization of technical and economic indicators of agents of remote control of ore quality; development of formal model of quantitative assessment of control risks in the ore-stream quality management system.

The real physical model of spatial iron concentration distribution in the ore yard area is of random nature. It is technically and technologically impossible to carry out direct control and measurement operations in different points of the "ore yard" area of 100x900 m. in the real environment. Therefore, this research proposes the use of unmanned aerial vehicles equipped with the necessary sensors, technical means of control and communication with a stationary local center for processing current on-board information (DPC) (Fig. 1). The number of control points is measured by the ratio S/Δ, where: S=L*M; L-length of the ore yard; M-width of the ore yard, S-area of the ore yard, Δ-distance between control points.

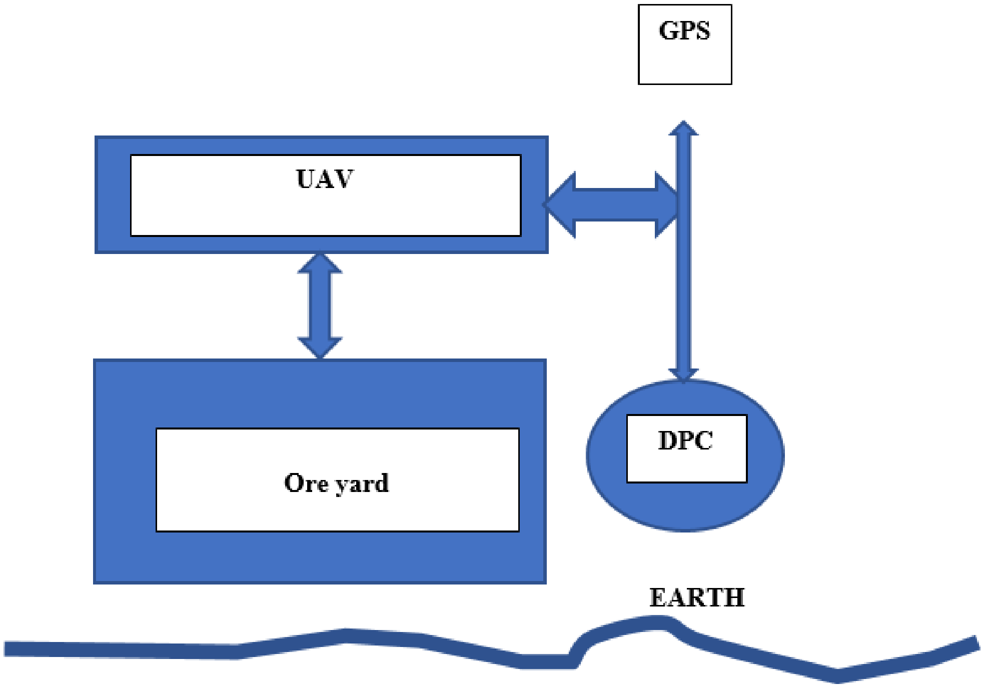

Fig. 1. Functional-technological model of the system for remote monitoring of iron ore quality.

The use of an unmanned vehicle significantly simplifies control and measurement operations, increases the manufacturability of control, but increases the cost of the project [11]. The proposed technological model transforms the continuous magnetic field of the ore yard into a digital controlled equivalent. The array of control and measurement information will be represented by a virtual digital spatial-information digital field (model), which is shown in Fig. 2.

$\{H_{n,1}\}$	$\{H_{n,2}\}$	……..	$\{H_{n,m}\}$
…….	……	……..	…….
……..	…….	…….	………
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…….	……..	…….	…….
$\{H_{1,1}\}$	$\{H_{1,2}\}$	……..	$\{H_{1,m}\}$

Fig. 2. Digital 2D model of magnetic field strength values in the ore yard area.

Each element of the information array contains the result of measuring a separate digital equivalent of the magnetic field values H_{ij} in some coordinate x_{ij} of the ore yard surface. The array size is determined by the requirements to the control accuracy, which depends on the number of elements on the digital field area. The total number of digital H_{ij} on the area of the ore yard (field) is determined from the expression N=M*L/Δ. Sampling intervals Δ can be set manually by the operator. The maximum value of the sampling parameters is determined by the positioning accuracy of the unmanned vehicle.

B. *Optimisation of Technical and Economic Indicators of ore-stream Quality Control Agents*

The final practical result of this research is software applications, the use of which allows quantitative assessment of producer risks and consumer risks in probabilistic form. It is also presented the possibility of assessing the reliability of control under given statistical laws and characteristics of random control agents. As it was established, control risks are functions of statistical parameters. Having preliminary or reported experimental material in a particular practical project, it is possible to solve the control problem in an optimal way under given metrological and resource limitations at the initial stage of work. It is also possible to solve the reverse problem, when metrological indicators of the used system support are specified and quantitatively known, and also norms and regulations are specified, then it is possible to quantitatively predict the quality of control by the sought indicators of reliability and risks. Quantitative values of producer and consumer risks have limited economic or social potential. Each investment project or business plan is completed with specific financial estimates, usually in monetary terms. Such a problem with specific economic calculations acquires an econometric form. In this paper the term ‘econometrics’ is interpreted as “Econometrics is one of the most effective controlling tools”. In some economic literature this term is given a more extended interpretation: “Statistical analysis of economic data is called econometrics, which literally means: the science of economic measurement” [12]. The use of econometric approaches to the proposed subject study opens up the possibility of optimizing the metrological indicators of the ore-stream quality control system. In similar problems, which were solved by a number of researchers in the field of technical diagnostics, the following logic of analysis was proposed [7]:

- Control and measurement works require certain costs for instrumentation (instruments), premises, consumables, staff salaries, computer equipment, etc.
- The cost of metrological support depends on the accuracy of measurements, as established in practice, in an exponential way.
- As measurements become more accurate, the lower the risks of control, and the subsequent economic losses associated with the risks.

This approach has the following graphical interpretation (Fig. 3) [4,5,16].

The main labor intensity in the implementation of such an approach to the optimal solution of the problem on the example of ore-stream quality control in real conditions consists in the organization and carrying out of experimental and statistical researches and further empirical formalization of integral and element-by-element economic costs and predicted benefits in quantitative measurement. In analytical form, the graphical model (Fig. 3) will have the following interpretation:

$$Ctot = Ccosts + Closses , \quad (2)$$

Ccosts costs include: the cost of the quadrocopter with the Cqu hanging tool, the cost of the magnetometer Cmag, the cost of the digital control system Cc, the cost of the maintenance system Cm, the cost of in-house technical staff Ci, and the cost of the software Cs.

A significant part of the total costs is the price of the quadrocopter together with the equipment and technical support of the entire unmanned system. Research and analysis of the UAV market by criteria of cost, reliability, operational and target efficiency showed that the market offers a very large price range of UAVs adapted for various industrial and scientific purposes.

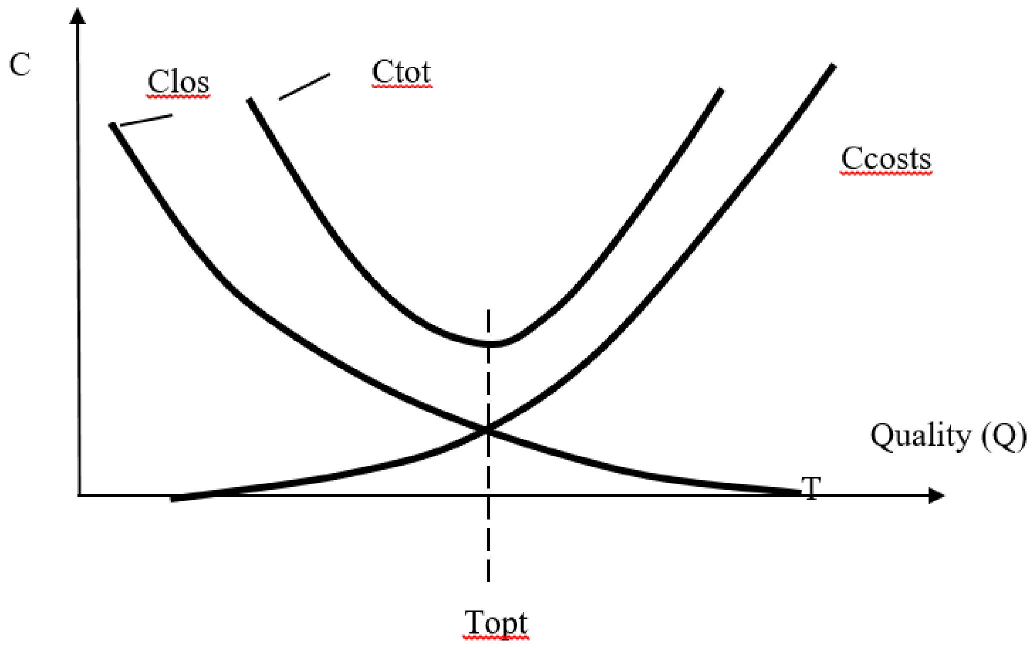

Fig. 3. Graphical model of risk optimization as a function of control accuracy [7]. C - costs; Ctot - total costs; Clos - losses from the reduction of control accuracy; Ccosts - costs of acquisition and operation of control and measuring equipment; T - control accuracy; Topt - optimal accuracy.

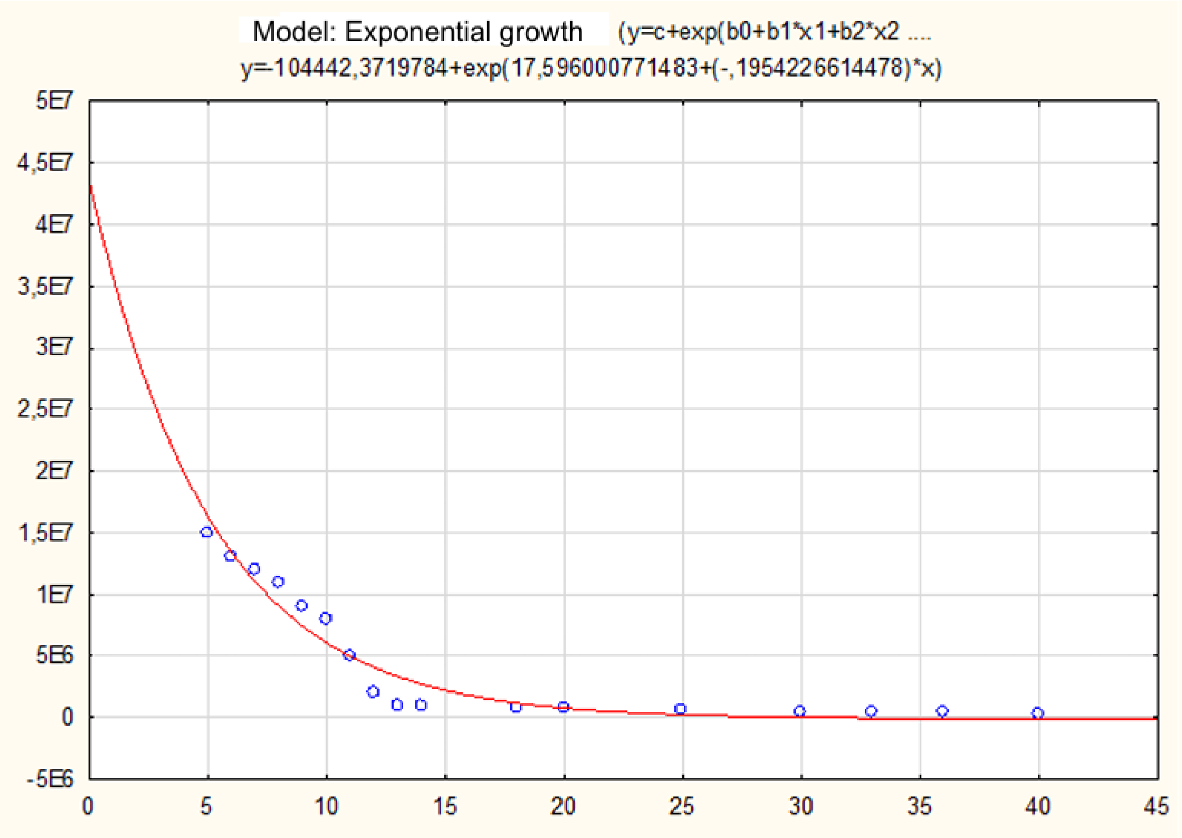

Fig. 4. Cost of tools and software in the ore-stream quality control and monitoring system.

An important economic component in the total production costs is the cost of the measuring complex, which includes: the cost of the magnetometer, the cost of premises for maintenance of the unmanned system, the cost of instrumental and information-measuring support for maintaining the operational reliability of the entire ore-stream quality monitoring system, the cost of maintenance personnel. As follows from the materials presented above, control risks and losses in the function of risk level are closely related to metrological indicators of the control and decision-making process at all stages of the life cycle of the system under research. According to the results of the analysis of Internet resources, literature sources, scientific and technical reports, the statistical material on this problem was collected, which after preliminary processing in the graphical design has the following form (Fig. 4):

The regression empirical approximation of the graphical model is as follows:

$$Ccosts = 104442{,}37+\exp(17.6-0.195V, \quad (3)$$

where V is the relative uncertainty of the control in percent (V= σl/Have, %).

In this model, the explained proportion of variance is 0.940, correlation coefficient R = 0.969, F=12.6.

The second component of expression (1) Closses quantifies the probable losses incurred by the business from emerging control risks in the digital control system in the form: Pfr - probability of producer risk and Pur - probability of consumer risk. Quantitative digital risk assessments can be referred to as virtual or augmented reality assessments. Giving these assessments a quantitative measurable economic content is one of the tasks in the ore-stream quality control system. The methodology of formal description of many technological processes and economic evaluation of losses at each of the process stages is an extremely difficult task in digital object control, since each agent of the investigated process is a “black box”.

C. *Development of a Precedent Model for Control Risk Assessment in Technology to Improve the Homogeneity and Averaging of Ore Material*

One of the labour-intensive process steps in metallurgy is ore averaging [13]. Ore averaging seems to be a very necessary technological process due to the fact that ore from different deposits is a multicomponent and dissimilar mineral structure. Process regulations for ore smelting are oriented towards a product with a certain tolerance percentage of a useful component, such as iron, in the range Femin to Femax, which corresponds to a magnetic field value in the range Hmin to Hmax. Ore transported from the mines is unloaded to the “ore yard” in layers and stacks in a certain order. The ore is taken by the excavator across the layers so that the grab grabs as many layers as possible at the same time, and already at this technological stage the ore shipped from the ore yard is averaged. On average, the stack capacity is 100 thousand tonnes and the number of layers is in the range of 300-1000. The magnetic field Hi(x,y) is monitored over the entire area with a certain metric step Δx;Δy. Two-dimensional address point H(i,j) is a spatial coordinate of a virtual area of L×M size. The number of information addresses is determined by the technical and technological capabilities of the magnetometer and UAV. The data information matrix will look as shown in Fig. 2. The accuracy of control is determined by the metrological indicators of the remote control system, which also includes the accuracy of UAV positioning and variability of the controlled parameter. The quality of homogeneity of the controlled ore environment in the operating mode is assessed operationally in the round-the-clock mode according to the established technological regulations with specified time intervals between control sessions. As noted above, most of the works consider modelling options where it was assumed that norms are deterministic values. Practice shows that this hypothesis simplifies the situation, which leads to significant methodological errors. This implies the necessity of building formal models taking into account the uncertainty of norms, which seems to be a precedent approach [14,15].

Considering the control system as a “black box”, norms should be considered as one of the components of this precedent system, which has a high degree of uncertainty. The statistical nature of norms, as an objective fact, has been considered in many works [5,6,7,8]. As a measurement error in these works it is proposed to use the value of uncertainty, which is quantified by the mean square deviation [16,17]. Uncertainty among the key factors of control and decision-making risks in the system of precedent management should be considered as a phenomenon and as a consequence of incomplete knowledge about the topic under study, i.e. as a factor of “black box”, a factor of environmental influences, unclear or inadequate understanding of objectives. The technical field has its own specificity and traditions, where the priority is given to instrumental metrology and, first of all, to measurement errors in the control system.

In the proposed research, priority in the ore-stream quality management system is also given to the uncertainty of norms, which are considered in formal models as random variables having different distribution laws. Possible management risks are investigated in the pre-project stages, and subsequently at some stages of the life cycle as required. As a rule, risk research is carried out in many practices at a qualitative level. However, in production reality, economic and other projected losses are of practical value only if they are quantified.

From all the above theoretical and practical material, in relation to the subject area under study, there arises the need and the task of quantifying the impact of the statistical nature of the tolerance field on the quality of control, and as a consequence on the quality of the ore-stream control system, under conditions of statistical uncertainty of agents and control precedents [18].

Without giving intermediate conclusions, the probable number of objects erroneously rejected from the whole sample N is expressed by the following formula [5]

$$N_{fr} = \sum_{i=0}^{m} N \int_{Li}^{Hi} \theta(Bl)dBl \left[\sum_{j=0}^{k} \frac{1}{\sqrt{2\pi}} \int_{\theta_i}^{\lambda_i} e^{-\frac{t^2}{2}} dt \times \frac{1}{\sqrt{2\pi}} \int_{\frac{3j}{k}}^{3} e^{-\frac{z^2}{2}} dt\right], \quad (3)$$

The likely number of undetected reject results will be:

$$N_{ur} = \sum_{i=0}^{m} N \int_{Li}^{Hi} \theta(B)dB \left[\sum_{j=0}^{k} \frac{1}{\sqrt{2\pi}} \int_{\theta_i}^{\lambda_i} e^{-\frac{t^2}{2}} dt \times \frac{1}{\sqrt{2\pi}} \int_{\frac{3j}{k}}^{3} e^{-\frac{z^2}{2}} dt\right], \quad (4)$$

where the distribution density function of the normative value of the controlled parameter B has the following form and parameters:

$$\theta(Bl) = \frac{1}{\sqrt{2\pi} \cdot 6n} e^{-\frac{(Sn-Sal)^2}{62_n}}$$

Ϭn - standard deviation of the distribution density function of the normative value of the controlled parameter B;

Sal - arithmetic mean of the lower norm of the controlled parameter B.

Expressions (3-4) presented in such a probabilistic form have an extremely complex analytical structure, which will lead to a very high methodological error in numerical computer implementation. Therefore, the use of simulation modelling [19,20,21] is evidently recommended in the problems of this subject matter. With this in mind, a simulation model is developed and proposed in this research, the algorithm of which is shown in Fig. 5.

The logic and operation of the algorithm can be clearly read and understood from the functions of each of the model blocks. The work of the algorithm starts with the input of statistical model data: H_{ave};σ_u;σ_{meas};σ_l,σ_u;H_{lave},H_{uave}. The optimal number of simulation cycles is found experimentally. The simulation is completed by outputting the values of risk and control reliability

P_{fr}= N_{fr}/M and P_{ur} = N_{ur}/M,

Headings, or heads, are organizational devices that guide the reader through your paper. Where N_{fr} is the content of the false reject counter; N_{ur} is the content of the undetected reject counter; M is the total number of simulation tests.

The reliability D is calculated using the formula D = 1- (R_{fr} +R_{ur}).

A software application has been developed for quantitative calculations of control risks by computer modelling. Making quantitative simulation calculations at different compositions of statistical laws of distribution, it is possible to find out the degree of influence of forms of statistical distributions on the result, which will determine the scope of experimental research and the final reliability of the results. The final stage in the quantitative assessment of risks is to give them a quantitative economic content, which is discussed above.

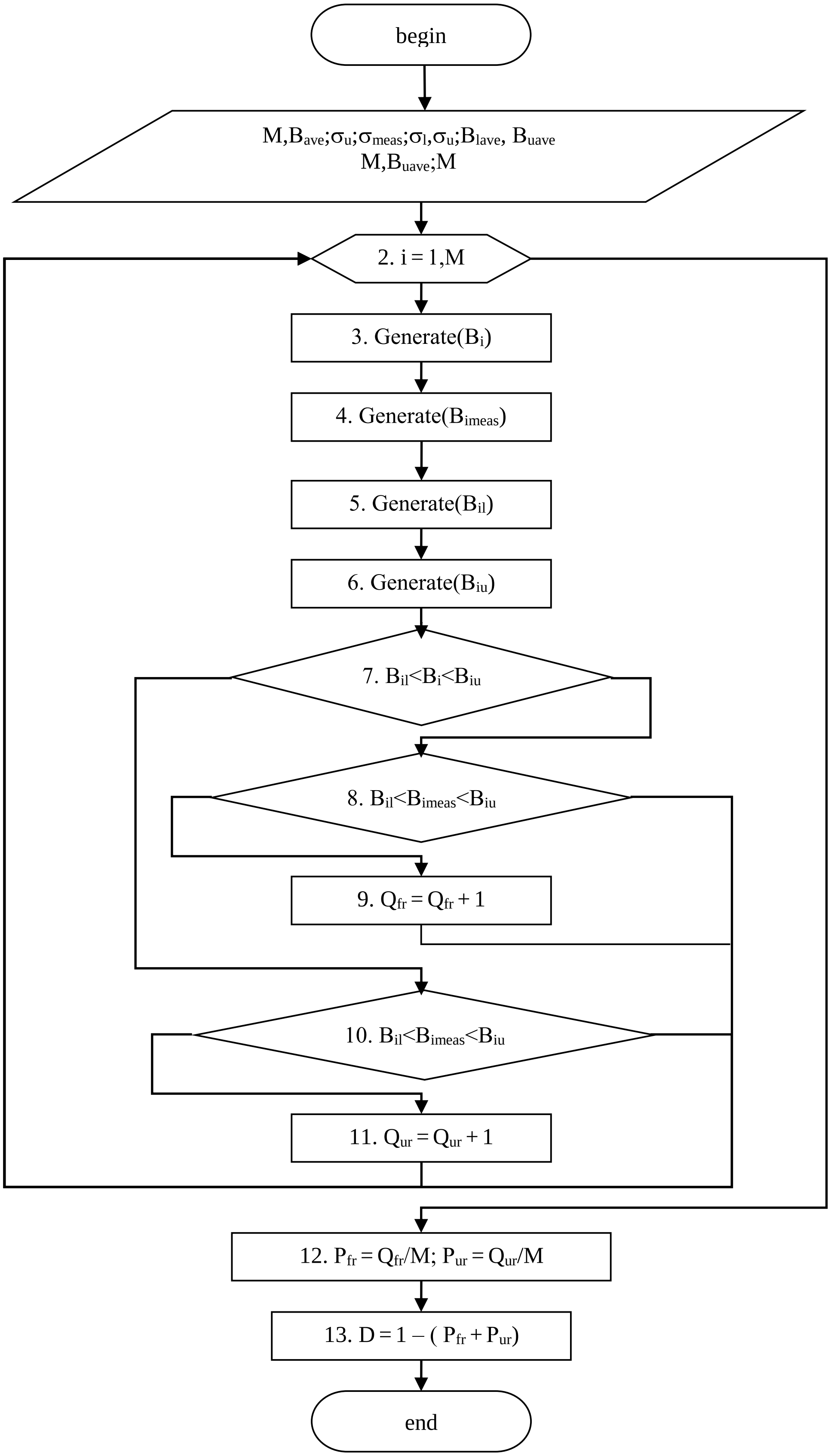

Fig. 5. Algorithm of simulation model for quantitative assessment of control risks under uncertainty of normative values.

VI. COMPUTER MODELLING

The software application [21] was used for computer modelling in order to obtain the calculated risk values for the ore consumer. The results of computer calculation of probable risks of P_{ur} control, under non-deterministic regulations are given in Table I.

P_{ur} control errors in commercial settlements between the producer and the consumer of ore depend on a variety of market factors. These factors include exchange prices for ore of a certain quality. Ore quality is primarily determined by the percentage iron content. It is common practice at the iron ore exchange to ration ore into three qualities levels - 40%, 50%, 60%. Ore of high quality (60%) may be quoted under separate situational rules with a high level of uncertainty.

To visualize the process of modelling data analysis, using expression 3, a 3D model of total costs in the ore-stream quality control system was built using P_{ur} risk as an example. The 3D modelling results are presented in Fig. 6.

As it follows from Fig. 6, the three-dimensional surface of total costs of Var3 in the system of risk management and quality control of ore-stream shows a clearly expressed area of minimum, which corresponds to the norm of iron content in ore material equal to 40%.

To quantitatively analyze the results of modelling, the total present value of probable monetary losses of the ore consumer as a function of control errors P_{ur} was estimated for the norm 40% and ore volume: V=1000000 t (cost Cdol/t=100) (Table II).

TABLE I. RESULT OF COMPUTER MODELLING OF PROBABLE CONTROL RISKS P_{UR} (ORE CONSUMER RISK)

Technological rule of average iron content according to the level of magnetism in ore H_{ave},%	**Relative uncertainty of ore grade control, σ/H_{ave}**								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
P_{ur} (%) at iron content rate H_{ave}>=40%	2.1	3.3	4.5	12.9	17.15	20.5	24.0	28.1	30.2

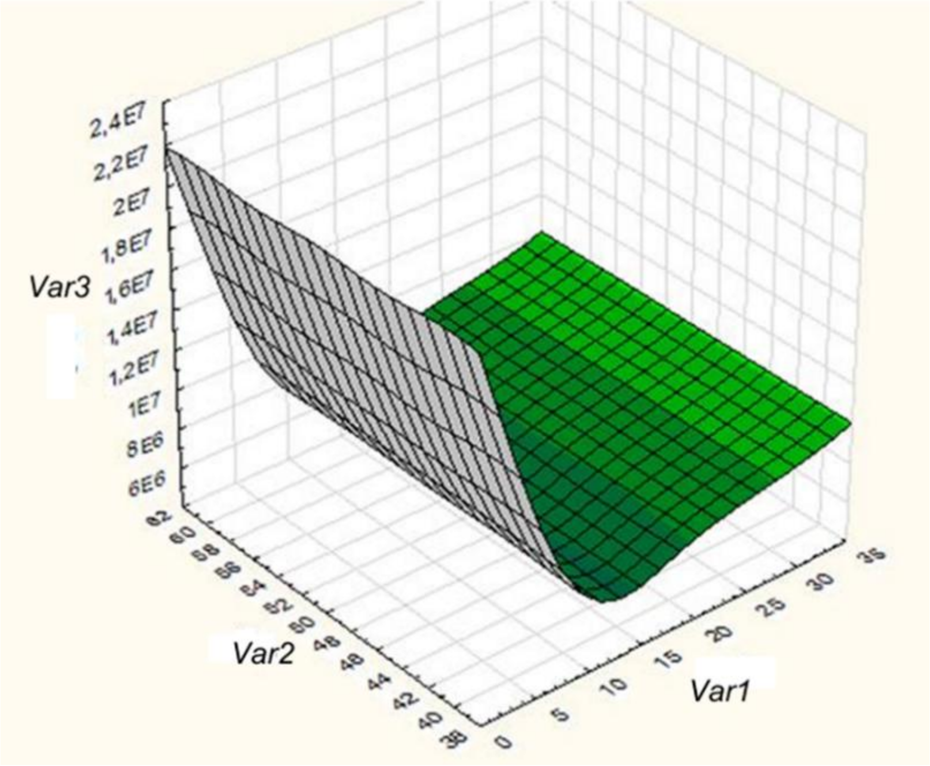

Fig. 6. Results of 3D modelling of total costs in the ore-stream quality control system. Var3 - total costs as a function of control accuracy and norms value; Var2 - norms value; Var1 - control uncertainty (accuracy).

TABLE II. TOTAL PRESENT VALUE OF PROBABLE MONETARY LOSSES OF THE ORE CONSUMER AS A FUNCTION OF CONTROL ERRORS P_{UR} FOR THE NORM OF 40% AND ORE VOLUME:V=1000000 TONNES (COST CDOL/T=100)

Average iron content rate by magnetism level in ore H_{ave},%	Relative uncertainty of control (σ/H_{ave})					
	0.1	0.2	0.3	0.4	0.5	0.6
P_{ur} (%) at iron content rate H_{ave}>=40%	15000000	9000000	5000000	6770000	7450000	8300000

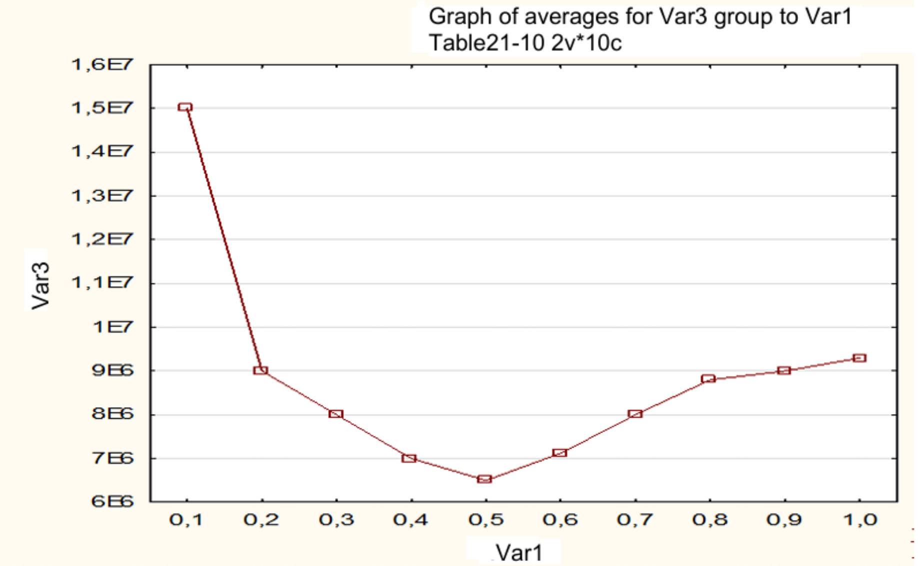

Fig. 7. Graphical 2D Model for Estimating Ore Consumer Monetary Losses as a Function of Control Errors (Consumer Risk). Var3 Financial Losses due to Probable Risk P_{ur}, as a Function of Relative Control Uncertainty σ/H_{ave} (Var1) for the Norm of 40%.

Fig. 7 illustrates a graphical 2D model for estimating ore consumer monetary losses as a function of control errors (consumer risk) at a norm of 40%.

As follows from Fig. 7, the minimum of total losses in the ore-stream quality control system as a function of the accuracy of iron content control in the ore material corresponds to the ratio $\sigma/H_{ave} = 0.5$. Here σ is the mean square deviation of the measurement error of the iron content in the ore material, and H_{ave} is the average value of the controlled magnetic field strength of the ore material with a norm of 40%.

VII. CONCLUSION

According to the modelling results, it was found that the ore-stream quality management system is a multifactorial process in which the key function is control. The total costs of ensuring effective digital control contain: purchase and maintenance of instrumental means of measurement; losses in the function of control quality assessed by control risks. The total cost of ensuring effective digital control has a close correlation with control and measurement risks, which determine economic losses in the ore-stream management system. Adequate assessment and forecasting of risks, as well as economic consequences of control is possible through mathematical modelling based on the data of experimental and statistical researches.

As a result of experimental researches and computer modelling, the optimal ratio of the cost of control and measuring equipment depending on metrological indicators, normative regulations for the initial ore material and statistical properties of the controlled ore material was revealed.

In the conditions of competition, developed inter-corporate and international relations and a number of other factors, an objective quantitative assessment of the economic efficiency of new innovation projects in practice seems possible with a formalized quantitative calculation of total costs and losses as a function of the accuracy of control and decision-making.

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