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INTRODUCTION

Enterprises of the mining and metallurgical branch of industry represent a system-forming segment of the economy of Ukraine and the replenishment of its currency reserves of the state [4].

However, due to the complication of the process of iron ore mining, the cost of iron ore increases due to the fact that the mining depth of this type of mineral increases. At the same time, there are not so many options for its growth, not to mention its decrease, within the existing technologies of iron ore extraction. The option of reducing the energy intensity of iron ore mining is relevant and realistic, which will give a real opportunity to stabilize the economy of these types of enterprises and their competitiveness on the world market of raw materials at a positive level.

A trivial way in this direction - to increase the level of energy efficiency of mining enterprises, is the replacement of existing technological equipment with electrified types of mechanisms for modern energy-efficient and energy-saving ones. However, the effect, which is actually achievable and achieved at mining enterprises from such a measure, is minimized in practice by the fact of increasing the depths of iron ore mining [7-13].

In the list of real direction measures, there is a change in the functioning parameters of the power supply systems of these enterprises by increasing their voltage levels - at least from 6 kV to 10 kV; from 0.4 kV to 0.6 kV.

However, all of the above, as well as a number of other unspecified directions in increasing the energy efficiency of iron ore mining, do not represent the measures that will allow to obtain the final solution of the desired and possibly achievable level of efficiency. And it is precisely such a solution option that should be the horizon to reach which you need to direct the vector of your searches.

For this, the strategy of solutions, as an equivalent process, should be developed from the very beginning at the level of a preventive vision of the fact of the necessary reassessment and expansion of the existing boundaries of the research format for solving the problem being analyzed, with a new vision of both segmental solutions of the entire multifunctional complex and the final aggregative option.

Relevance and main directions of scientific research in the direction of increasing the energy efficiency of underground iron ore mining.

Traditionally, in mining enterprises, the technology of ore extraction is a continuous process, which is based on the functioning of technological equipment - mining machines and mechanisms, the work schedule of which is regulated within rather narrow time limits and depends on the planned, at least monthly, production volumes. At the same time, the cost of electric energy in the formation of the iron ore production cost complex is taken on the basis of indirect indicators of the past months or days. With the existing three-zone tariffing with differentiation according to the hours of the day until 2019, which was in effect before the introduction of the Law of Ukraine [20], energy consumption levels at enterprises, where possible, were tried to be reduced during the hours of peak and semi-peak tariffs. After the implementation of the hourly daily electricity market, when its planned price changes hourly, and the time when the price is high does not coincide from day to day, it is quite difficult to save material payments for the consumed electric energy in this way, because both before and now as such a necessary level of control of electricity consumption according to tariff levels did not exist and does not exist, or this process is carried out in a manual control option.

Over time, as a fact of the present, the problem of managing this process has become even more acute. In such a situation, the simple leveling in hours of the day of the levels of electrical energy consumption, and, therefore, the operating modes of technological machines and mechanisms, has its strict limitation - the planned volumes of production - iron ore extraction, which are pre-planned by the enterprise, including the current ones for each day in advance. In this way, a multi-criteria task is formed to solve the problem: the operation of the equipment to the maximum possible in the economic daily tariffs of the zones with the implementation of planned tasks for the extraction of iron ore. In such an uncomplicated, at first glance, option, the fact that the volumes of iron ore production are not always stable and, as a rule, can change in accordance with the orders of importers for delivery volumes, is important and, at the same time, difficult for obtaining a final decision. In the case of manual control of this process, such control cannot be effective. A project of an actual solution is emerging - the development of ACS for managing this process. However, the system-forming factor of the effectiveness of the functioning of such an ACS, that is, the development of the ACS work format, or, more precisely, the algorithm of its work, should be understood as that, based on the fact of the stochasticity of the process of electricity consumption by receivers of iron ore mines (which will be proved later), the control be carried out on the ACS platform with the involvement of artificial intelligence in this process [21-25].

At the same time, for the theoretical justification of this direction with the real level of the expected effect, the first step should be the development of the format of the system that will be subjected to research. Regarding the research strategy in this case, this research format looks like a complex: electricity supply - electricity consumption. In turn, two side criteria should be analyzed and evaluated in this research complex: the quality of electricity supply and the quality or efficiency of electricity consumption. At the same time, it should be understood that the quality of power supply is not the quality of electrical energy, but the quality of electrical energy is a component of the quality of electrical power supply. Moreover, taking into account the above-mentioned fact that the modes of operation of technological machines and mechanisms as electrified types of consumers of electrical energy of mining enterprises are not characterized by the stability of their functioning, the emphasis for achieving the necessary level of efficiency of such a complex should be a controlled process, which should be based on the implementation of the appropriate algorithm for working with the assessment process and subsequent management according to multi-criteria variants of input parameters.

This formula applies to all types of electric energy consumption of these types of enterprises, but it acquires a special nuance of necessity and complexity of its solution in relation to consumers of electric energy with a supply voltage of up to 1000 V. These consumers of iron ore enterprises are characterized by their variety of types and modes of operation [26, 27]. These arguments form the difference in the formats of complexes: electricity supply - electricity consumption both in the PSS structures of electricity consumers and in the list of their nomenclature and unit capacities between enterprises with underground methods of iron ore extraction and others related to the extraction of other types of minerals, including coal.

The width of the known measures to increase the energy efficiency of iron ore mining is sufficient to perceive the importance of the problem, but the level of results of their impact on the final version of the solutions is different, and in some versions it is completely insignificant, or even negative. Therefore, the formatting of solutions that can be achieved in terms of efficiency as a basis for developing research tactics to find modern effective measures to increase the energy efficiency of mining enterprises with underground methods of iron ore extraction is a priority task from the list of directions for the next search.

That is, summarizing the motivations presented above, it is logical to conclude that functionally the electric power complex of iron ore enterprises represents a complex functional synthesis with complex electro technological processes and with certain individual and, at the same time, system-forming segments. Taking this statement into account, the process of this scientific research was formed.

The purpose of the research is to develop theoretical aspects and practical recommendations for increasing the energy efficiency of the functioning of complexes: electricity supply - electricity consumption with a supply voltage of up to 1000 V by managing this process in the conditions of mining enterprises with underground methods of iron ore extraction.

However, as research shows, the development of such a variant of increasing the energy efficiency of iron ore mining is a non-trivial task with a significant number of input parameters that must be evaluated and adequately responded to in the format of managing this process. The idea of creating an automated system (ACS) of the electrical energy processes of these types of enterprises appears to be an alternative option for such a solution. In turn, the system-forming moment of the creation of such an ACS format is the need to format the electric power complex in the combined aggregative version of the functioning of electricity supply - electricity consumption.

In turn, the development of such an ACS variant is not possible without a careful consideration of the variability of its functioning processes as a function of a number of stochastic changes in input parameters with the need for a minimal time adaptive response of the control actions of the system.

Such a result - the ACS control algorithm can be achieved by appropriate modeling of the operation of this system according to options for changing the input parameters.

SECTION 1.
ANALYSIS OF ENERGY-ORIENTED MODES OF ELECTRICITY SUPPLY TO IRON ORE MINES AS A SCIENTIFIC RESEARCH OBJECT)

1.1 Research of the state of the electric power complex: power supply - electric consumption of iron ore mines

Increasing the efficiency of electricity use in the methodological aspect in the conditions of the further development of mining and ore industries dictates the advocacy of the development of the theory of repurposing power supply systems to new modern languages of functioning of the synthesized power complex: power supply-power consumption. To analyze and evaluate processes in this format of the electric power complex, it is necessary to develop new scientific approaches and methods of state assessment, analysis, modeling and forecasting of the entire process mentioned above, in the existing conditions of uncertainty and incompleteness of information and, most importantly, development in the final version ACS by this process.

However, at the start of such development, it is necessary to decide on the format of the input parameters for both evaluation and management of this complex power plant, which is difficult to operate.

In this connection and according to the research task of this dissertation, it is appropriate to consider. Evaluate and choose methods of evaluation, modeling and forecasting of the analyzed process.

When developing research logistics, it should be taken into account that the search for effective measures to increase the energy efficiency of electric energy complexes of mining enterprises with underground methods of iron ore raw material extraction is inextricably linked with the problem of the level of reality in assessing the modes of electricity consumption by the relevant consumers and, what is especially relevant and necessary, the determination of influencing factors to this process, the specifics of the technology of conducting mining operations at this or that enterprise.

To form such a basis for the logic of research and analysis, we consider it expedient to conduct active experiments in the conditions of operating enterprises.

According to the results of known studies of the analyzed processes and preventive scientific research, which will be presented in this section, the following areas of research of this process are appropriate:

electricity consumption of mining enterprises depends on a significant number of factors, the influence on the process of electricity supply - electricity consumption, which has a complex and diverse nature, and the description within the framework of both deterministic and classical statistical methods is not always possible due to the unpredictability of the conditions that determine the levels of influence of these factors on the functioning of receivers and, accordingly, on the process of electricity consumption. We note that the levels of electricity consumption of iron ore enterprises are formed under the influence of factors, the trivial prediction of whose influence is not sufficiently reliable. Moreover, the significant number and variety of these factors poses certain difficulties in assessing the effect of the level of their influence on electricity consumption in both methodological and technical-economic aspects.

Information about the process of electricity supply and electricity consumption of underground mining enterprises contains various sets of empirical data and characterizes it as multidimensional. A significant number of such signs of influence make the task of identifying the connections between them difficult to solve. In this case, a description of the process is required: electricity supply-electricity consumption with as few generalized characteristics as possible, which reflect internal objectively existing patterns that cannot be directly observed even within the framework of an active experiment.

The specified features lead to the need to use in the assessment of the states of the modes: electricity supply-electricity consumption of mining enterprises, methods that allow obtaining solutions under conditions of incomplete information in case of a decrease in the dimension of the initial data about the research object. In this case, there are tasks of analyzing data on electric energy consumption, the solution of which is based on the application of factor analysis methods and the establishment of a typology of the studied objects.

In this aspect, the assessment of the state of the power supply-power consumption process with all the variety of analysis models is based on the premise that during a survey or experiment, when the empirical material contains a large number of parameters, a significant number of which are connected by correlations. At the same time, it is taken into account that the observed "external" parameters only indirectly characterize the analyzed process. At the same time, it is important that along with a large number of "external" parameters (factors), there is a system-forming number of "internal" parameters that are difficult or even impossible to measure or calculate, but they largely determine the behavior of "external" parameters. Finding these hypothetical essential parameters and evaluating the levels of their influence is the goal of analyzing the state of the process.

It has been established that such parameters (factors) of mining enterprises, such as the depth of the ore body, the size of the deposits, the temperature in the underground workings, the type of iron ore extraction technology, the parameters of the development and extraction systems, the types of machines and equipment used, and others, affect the level energy consumption of iron ore products. In turn, electric energy factors also influence - structural parameters of electrical circuits, number, power efficiency. electrical receivers and others, which determines the formation of electric load regimes. Organizational and operational factors determine the degree of use of electrical receivers. The level of increased losses of electricity due to the deterioration of the characteristics of electrical equipment, machines and mechanisms. In this, it is advisable to investigate the main procedures for assessing the states of power supply modes, taking into account real experimental information.

Figure 1.1 shows a general methodological approach to the study of the power consumption process.

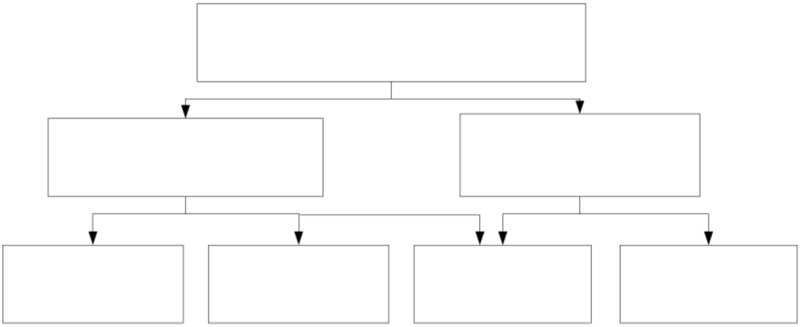

Figure 1.1 Structural and logical diagram of the study of the power consumption process

Electricity consumption by machines, mechanisms, installations is characterized by electricity consumption modes, electricity consumption per unit of production of iron ore. In this regard, when examining electricity consumption by machines, mechanisms, and installations, it is advisable to establish: the main regularities of the formation of power supply schedules.

Analyzing electricity consumption processes

receivers of iron ore mines, in order to sufficiently perceive the necessity and importance of this procedure in the further development of research tactics, it is considered necessary to formalize the entire consumer electrical complex with its subsequent equivalence by types of components of the electricity consumption process.

Figure 1.2 shows the average distribution of electricity consumption levels between consumers in the case of underground iron ore mining.

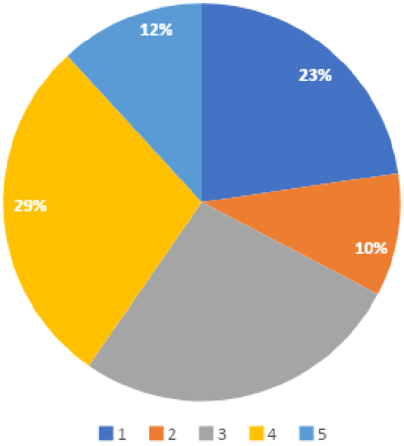

Figure 1.2 Distribution of levels of electricity consumption among consumers in the underground method of iron ore mining

As evidenced by the data in Fig. 1.2, in addition to individual energy-intensive consumers of electricity (skip lifting installations, drainage complex and main ventilation installations), about 20% of electricity is consumed by underground receivers with a supply voltage of up to 1000 V. However, for the necessary level of disclosure of the condition, it is necessary to know and evaluate the real modes electricity consumption process. This applies both to all electricity receivers in general, and to energy-intensive types separately.

In turn, the assessment of electricity consumption modes by receivers of enterprise data should be considered as a system-creating component of input parameters for the development of a management algorithm for managing this process, which should be synthesized to manage the entire consumer complex of the enterprise with a differentiation for each consumer from the corresponding group.

Figure 1.2 shows typical graphs of electricity consumption of relevant energy-intensive consumers borrowed from well-known previous research by searchers, which are the basis for developing tactics for management. As evidenced by the graphs of fig. 1.2 levels of fluctuations are characterized by a significant range and are stochastic in nature, which once again forms the logical necessity of managing this process and is not the purpose of the author's research.

According to the outlined goal of this scientific search, in the future, exclusively electrical energy processes will be analyzed in the components of PSS - district substations with a supply voltage of up to 1000 V of the general power supply system of an iron ore mine. For this purpose, about 50 registers of daily schedules of transformer loads of a number of DUS mines were experimented and processed to determine the real basic output power parameters of DUS.

In order to achieve the necessary reality and reliability in the construction of electrical loads, experimental studies were conducted in the mines of the Kryvyi Rih iron ore basin for a number of years, and experiments from the archives of the Kryvyi Rih National University were also used.

Based on the data obtained in this way, the actual schedules of DUS loads were constructed and the load characteristics were determined.

To illustrate the magnitude and nature of the loads (Figs. 1.3-1.5), daily graphs of the load of the DUS transformers of individual mines during the busiest days are given during the experiment in a number of mines.

The analysis of the obtained data gives reason to assert. That the process of power consumption by DUS receivers is stochastic in nature. Thus, thorough formalized processing requires more in-depth, systematic ones. scientific and innovative research approaches and methods.

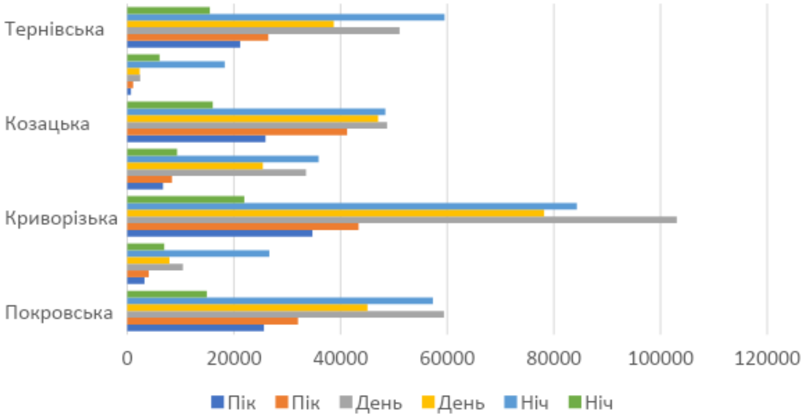

Figure 1.3 Daily levels of electricity consumption and the corresponding cost at iron ore mines of the Kryvyi Rih Basin (2021)

The author also investigated the ratio of components of the electricity consumption system from the point of view of consumers (Figs. 1.3 - 1.5).

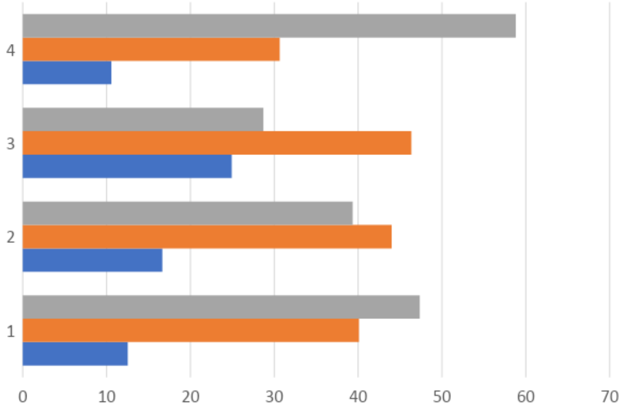

Figure 1.3 Ratio of components of the power consumption system mine "Ternivska".

In fig. 1.4 presents a more detailed visualization of consumers and the corresponding capacity of UPP - 3 (section 2) of the Arcelor Mittal mine (Kryvyi Rih)

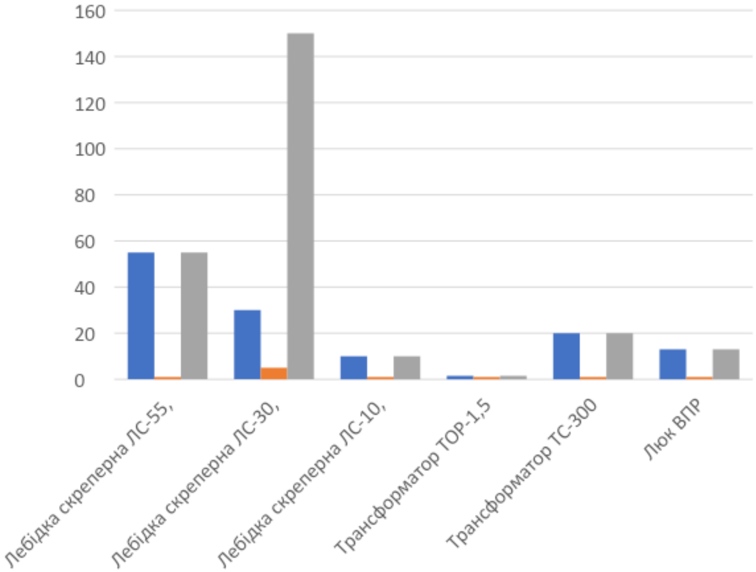

Figure 1.4 UPP consumers - 3 (section 2) sh. Arcelor Mittal (Kryvyi Rih)

A similar analysis was carried out for the Kozatska and Pokrovska mines. Accordingly, in order to monitor the dynamics, the average daily consumption and cost of electricity were calculated for the years of the Giant-deep mine (Table 1.1).

In the opinion of the author, a more in-depth study of the state of operation of the electric power complex: electricity supply - electricity consumption of iron ore mines should be carried out on the basis of information obtained as a result of direct experiments at a real iron ore enterprise, namely on a separate mine, since the results of experimental studies indicate significant discrepancies in the analyzed results between one and another mine.

Table 1.1

Average daily consumption and cost of electricity over the years of the Gigant mine

№	**Indexes**	**Years**			
		2013	2018	2019	2020
1	Average daily electricity consumption, kWh	2302	2124	2405	1863
2	Average daily cost of electricity, UAH	1245	2016	2961	2664
3	Average daily specific cost of electricity, UAH/kWh	0,541	0,949	1,231	1,430

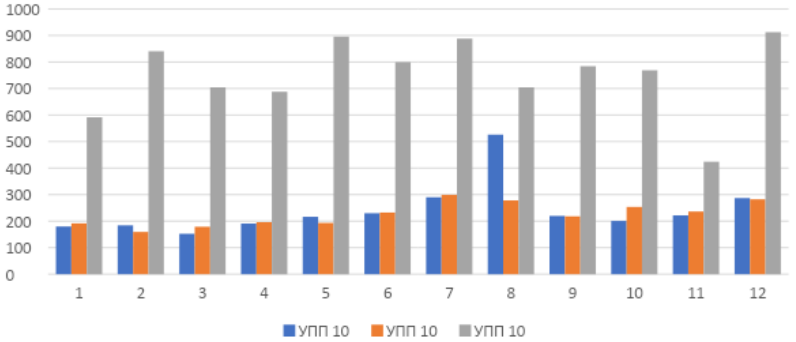

Figure 1.5 Graphs of daily consumption (31.01.2021) of electric energy of the Saksagan mine (Kryvyi Rih)

As evidenced by the obtained results, fluctuations in the levels of electricity consumption by DUS consumers, as well as stationary installations, have a sharply fluctuating nature.

As shown by studies [1, 2, 3, 4, etc.], a significant number of technological power receivers of mining enterprises form energy regimes that have a heterogeneous (from the point of view of probability distribution) character. "concise") information about power consumption processes are multimodal in nature. This circumstance introduces certain difficulties in the modeling of power consumption processes.

In the case of non-homogeneous energy mode of operation of electric receivers (with multimodal distribution of electric load values), it is advisable to model the power consumption process by selecting stable levels from the entire area of load changes, near the average values of which individual random load values change with a certain degree of dispersion.

The graphs (Fig. 1.2 - 1.5) show the technology of the functioning of consumers - three-shift work. In certain time intervals, the reactive power exceeds the active power, which indicates an overload of the equipment, albeit for a short time. According to experimental data, the group coefficient of use in different conditions varies between 0,1 and 0,2. In the process of experimental studies, the power coefficient tgΨ was also determined, which varied within 0,8-0,9 for different areas.

The analysis shows, or rather confirms the conclusions of previous studies, that the loading of transformers on DUS is less than 30% of the installed capacity.

The list of DUS electricity consumers, as mentioned earlier, includes consumers with a voltage of up to 1000 V. They include machines and mechanisms directly involved in the extraction of iron ore and those that conduct the process of preparing mine workings, as well as traction underground substations and others.

It is these consumers, or more precisely, the iron ore mining systems of the enterprises where they are operated, that form their work modes, which means the level and nature of electricity consumption.

With all the variety of known methods, currently iron ore mines in Ukraine mainly use iron ore development and extraction systems where the main type of ore delivery is scraper. Development systems with a vibration start are used much less often, but the level of power consumption in these systems is less than with scraper delivery. Therefore, at this stage of the work, we will pay the main attention to the study of electricity consumption processes of district electricity consumers who use scraper delivery, since this main method of extracting iron ore in mines and mines is the most energy-intensive, which means that attention to it should be a priority.

In the practice of operation of iron ore mines, as a rule, scraper winches with an electric drive based on asynchronous electric motors with c.z. rotor power from 10 to 100 kW. However, in the vast majority of cases, LS-30 scraper winches with a capacity of 10 kW are used. These types of winches to the greatest extent satisfy the conditions of conducting mining works, and are widely used both in extractive and preparatory underground mining works.

Simultaneously with the iron ore extraction works, preparatory works are being carried out in the block, new sections and vaulting are being completed (cut). The same types of scraper winches are also used at the preparatory sites for rock cleaning, the number of which is of the same order as in the mining operations, and in the initial period of operation of the unit, even more.

The scraper winches of preparatory works receive power with a voltage of 0.4 kV from the same network as the winches of mining works.

Loading of ore accumulated after scraping at mining sites (blocks) into trolleys is carried out using vibrating hatches with electric motors with a power of 10-14 kW. Regardless of the total number of hatches in the orti-check-in, as a rule, only one is turned on at a time. The term of one-time operation of vibrating hatches is limited to the term of loading the electric locomotive carriages. Local ventilation fans are not often used in mining areas. Usually, ventilation is carried out due to the general mine depression or pneumatic ejectors.

Table 1.2

UPP consumers – 3 mines of Arcelor Mittal (Kryvyi Rih)

№ line	**What feeds**	**Name of consumers**	**Power, kW**	**Quantity, items**	**Total power, kW**
Section № 1					
2	Area №12, Bloc № 7	Scraper winch SW-55,	55	1	55
		Scraper winch SW-30,	30	5	150
		Scraper winch SW-10,	10	1	10
		Transformer TOR-1,5	1,5	1	1,5
		Transformer TC-300	20	1	20
		Hatch VPR	13	1	13
		Total			23.5
3	Bloc №16 lighting stretch	Hatch VPR	13	1	13
		Transformer TOR-1,5	1,5	7	10,5
		Total			23,5
		Total per section			273
Section № 2					
6	Bloc №8	Hatch VPR	13	1	13
		Transformer TOR-1,5	1,5	1	1,5
		Fan SVM-6	14	1	14
		Total			28.5
8	Area №1 Bloc №6	Scraper winch SW-55,	55	1	55
		Scraper winch SW-30,	30	3	90
		Scraper winch SW-10,	10	2	20
		Transformer TOR-1,5	1,5	1	1.5
		Transformer TC-300	20	1	20
		Total			186,5
		Total per section №2			215

Table 1.3

Consumers of DUS № 10 of the Yuvileyna Mine (Kryvyi Rih)

№ line	What feeds	Name of consumers	Power, kW	Quantity, items	Total power, kW
Section №1					
6	Ort 213	Vibrating feeder VPR Transformer TOR-1,5	14 1,5	1 1	14 1,5
7	Ort 217	Vibrating feeder VPR Scraper winch SW-30 Tansformer TSH Transformer TOR-1,5	14 30 4,5 1,5	1 2 1 1	14 60 4,5 1,5
		Total per section №1			95,5
Section №2					
1	Ort 217	Scraper winch SWC-30 Vibrating feeder VPR Transformer TOP-1,5 Transformer TS-300	30 14 1,5 20	8 1 4 1	240 14 6 20
		Total			280
1	Ort 205	Scraper winch SW-30 Vibrating feeder VPR Transformer TOP-1,5 Transformer TS-300 Boiler	30 14 1,5 20 3	10 1 3 1 1	300 14 4,5 20 3
		Total			341,5
1	Lighting	Transformer TSH	4,5	2	9
		Total per section №2			630

Electric energy is also consumed by lighting, welding transformers, drilling machines, which do not have a significant impact on the level of maximum loads.

Summarizing the conclusions regarding electrical receivers that receive power up to 1000 V from DUS transformers, it seems logical to conclude that the modes of operation of machines and mechanisms by various consumers of electricity, electromechanical systems that are analyzed, completely depends on the volume of iron ore mining, the volume of preparatory (cutting) work and wear continuous in the hours of the day in the corresponding blocks of underground horizons of iron ore mines.

The electrical equipment and power supply of underground mining works, its reliability and efficiency largely depends on the mining technical conditions of each individual mine, which significantly affects the operation of the technological equipment in general and the electrical equipment of the mine separately.

Due to this fact, the modes of operation of DUS electricity receivers differ from stationary installations - the main drainage complexes and the main ventilation installations of mines. It is this fact that is system-creating in the formation of the algorithm for managing electricity consumption modes by DUS consumers.

At the same time, analyzing the indicators of the distribution of electricity flows among consumers of iron ore mines, in the realities of the electricity supply process of these types of underground enterprises, we note, as a fact, the change in the levels of their electricity consumption segments over the years.

Thus, compared to 1990, the average percentage of electricity consumption by energy-intensive consumers of iron ore mines of the Kryvyi Rih iron ore basin has changed to the following state (table 1.4).

As evidenced by the data (Table 1.4), the indicators have changed, but according to points 5-7, these changes are insignificant and close to the level of 20%. Such "approach" should not bypass the problem of increasing the overall energy efficiency of these types of enterprises, especially. According to this indicator, points 1-4 are approaching the level of exhaustion of their potential.

Table 1.4

Average indicators of electricity consumption by iron ore mines of the Kryvyi Rih iron ore basin

№	**Type of electricity consumer**	**% of the total electricity consumption by the iron ore mine**		**Deviation % (+/-)**
		1990	2021	
1	The main drainage	11.1	36,6	(+) 229,7
2	Skip lift	34,8	23,5	(-)32,5
3	Fans of the main enterprise	15,6	23,1	(+)21,2
4	Central (district) compressor stations (CCS, DCS)	18,8	Removed from the records of electricity consumers of mines	
5	Intra-mine transport - electric rolling stock ore	6,5	3,8	(-)71
6	DSF	11,0	8,6	(-)2,4
7	Other	2,2	4,4	(+)2,2

1.2. Basic imperatives for monitoring the power supply system - electric consumption - iron ore production volumes

The complex of sources and means of collecting and processing information is one of the important elements of the management system of industrial enterprises in general and mines in particular. On the other hand, it is inappropriate to collect information that is not useful in the decision-making process, because it leads to an increase in the costs of the monitoring system and reduces the effectiveness of analytical activities. And, since the basis of decision-making is the past, present and future economic and technical condition of the mine, the main components of the monitoring system can be the indicators of its technical and economic condition in general and power supply in particular.

The existing monitoring systems mainly contain financial indicators, which makes them retrospectively oriented and does not allow forecasting the main current state parameters. Such a situation necessitates the use of more complex surveillance systems that allow comprehensive data analysis and synthesis of management actions.

But, at present, with all the diversity and availability of information collection, there are problems, both objective and subjective, with its collection, storage, and processing. This is especially true today in the conditions of such strategic objects of the state's industry as mining. Incomplete information on the indicators of the electricity supply system - electricity consumption - volumes of iron ore production, or its redundancy, untimely receipt of information, and other negative factors complicate a comprehensive assessment of the system.

In the author's opinion, monitoring should be considered as one of the more important, relatively independent links in the management cycle regarding the implementation of energy efficiency requirements. As part of the monitoring, actions are identified and evaluated regarding the implementation of electricity supply management measures. At the same time, feedback is provided, which provides information on the compliance of actual results with the goals of ensuring energy efficiency.

The task is to correctly assess the extent, direction and reasons for the deviation of the current situation and results from the set goals. These deviations are caused by the influence of various external and internal factors on the enterprise.

At the same time, it is worth noting that the form and content of the initial results of the monitoring of the mine's electricity supply are determined taking into account the information needs of its participants, that is, specialists participating in the monitoring. In our opinion, the main thing in monitoring is not to cover as many areas as possible, but to clearly and timely record their condition based on a predetermined set of signs.

Monitoring as a management function involves the collection of information, its comprehensive assessment and forecast based on the appropriate system of indicators. The need to implement this requirement is dictated by its focus on analysis and comparison of management results. The standardization of the information set also ensures the convenience of its search and fixation and provides monitoring properties of the information process.

Monitoring can also be characterized as an operational collection of data on complex phenomena and processes that can be described by a fairly small number of key, particularly important indicators for the purpose of operational diagnosis of the state of the research object in dynamics. Having emphasized the property of monitoring efficiency, it is possible to clarify the definition of monitoring as aimed at operational tracking and analysis of information movements occurring in the process of electricity supply.

The dynamism of the object, the possibility of danger in the process of its functioning and the dimensions of the danger determine the necessity and expediency of using monitoring for research, as well as the choice of one or another specific monitoring system. In addition, one more feature should be noted - the possibility of building a forecast of the development of one or another system in the absence of fluctuating deviations or force majeure circumstances, which gives monitoring a special value and significance from the point of view of a potential user.

With regard to mine power supply systems, we propose to distinguish three types of monitoring depending on its goals.

Informational - involves the structuring, accumulation and distribution of information on the electricity supply of mines. It involves the use of reporting information. Such information is structured as by place, date, time. Accumulation and distribution of information is carried out in reports.

Baseline or background - detection of new problems and hazards before they become aware of at the mine power management level. A rather constant observation is organized for the object of monitoring with the help of periodic measurement of indicators (indicators) that determine it quite completely. To implement this type of monitoring, any of the three possible features of comparison can be used. The choice of one or another option will be determined by the monitoring objectives.

Problematic - finding out patterns, processes, dangers of those problems that are known and relevant from the point of view of developing the mine's power supply management system.

From the point of view of systematicity, the monitoring of the condition of the mine's electricity supply can be considered not only as a collection of research methods, but also as a system that contains a certain set of elements. In accordance with the types of monitoring proposed by the author for the mine's electricity supply, a study was conducted at the operating enterprises of Kryvbas according to the following indicators: date; time; power supply (active energy); supply; production (Fig. 1.6-1.9).

The choice of indicators was based on the existing mine reporting, which forms the basis of monitoring activities to ensure effective management of the power supply process of the underground iron ore enterprise.

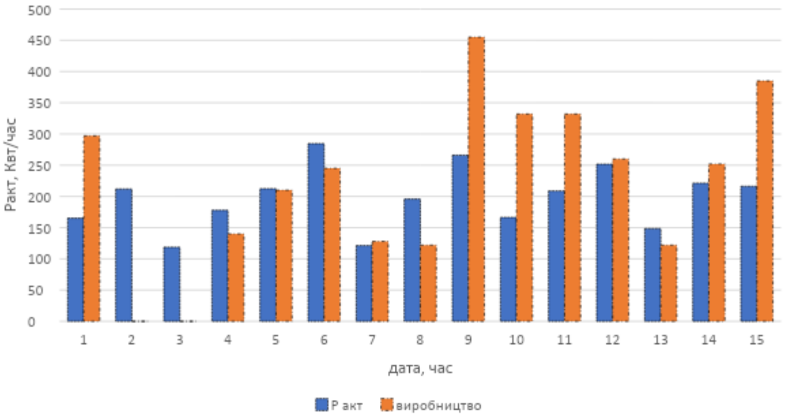

Figure 1.6 Monitoring of the electrical energy supply system – production of the "Mittal Still" Kryvyi Rih mine for transformer 1 UPP

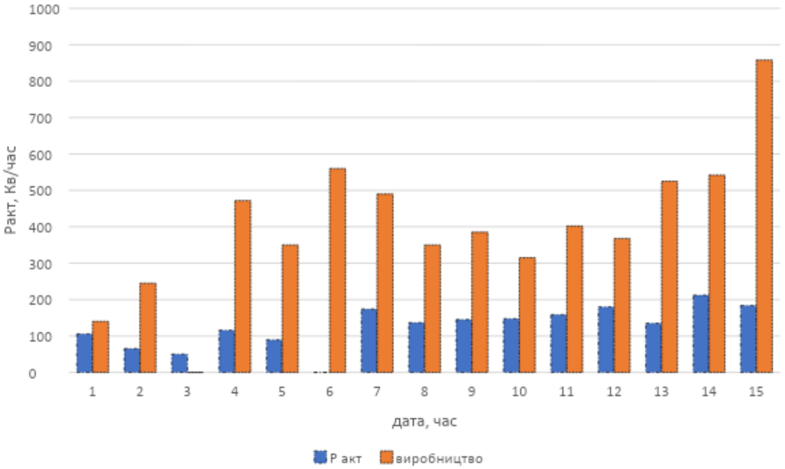

Figure 1.7 Monitoring of the power supply system - production for the "Mittal Still" Kryvyi Rih plant for transformer 2

The analysis of the presented graphic visualizations allows us to reach the following conclusions for the transformer1 (Fig. 1.6):

As of July 11 2021, despite the availability of electricity, there is practically no production. Of interest is the ratio of electricity supply - production according to the dates from 07/15/2021 to 07/18/2021, where production increases with a decrease in electricity supply. In general, electricity supply is noted as a wave-like process in time. The highest value corresponds to the time of day from 11 pm to 6 am.

For transformer 2 (Fig. 1.8). The power supply, unlike the transformer1, has an almost uniform, stable state with small differences in the period from 07/11/2021 to 07/14/2021. You can note the date 07/15/2021, when the power supply decreases between 11 p.m. and 6 a.m., and production increases. The date 07/18/2021 is characterized by the same ratio.

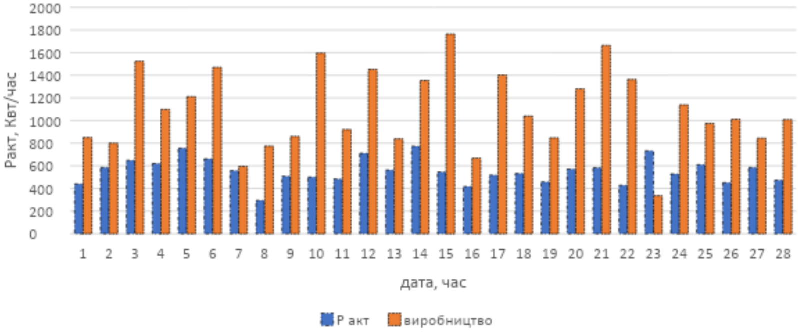

Figure 1.8 Monitoring of the power supply system - production for the Tsentralna mine for transformer 1 of the Yuvileyna mine, Kryvyi Rih

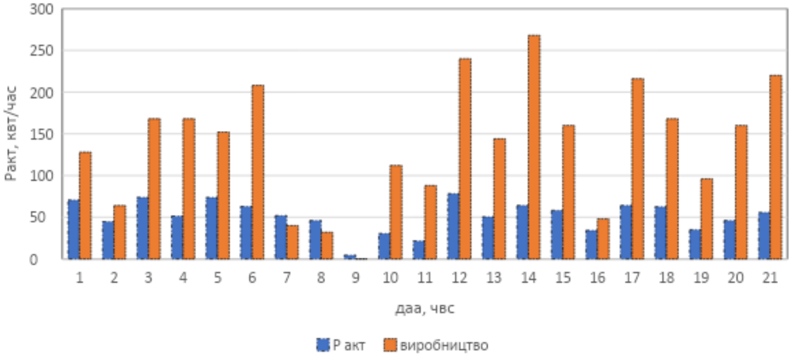

Figure 1.9 Monitoring of the power supply system - production for the Tsentralna mine for transformer 2 of the Yuvileyna mine, Kryvyi Rih

Data visualization of fig. 1.9 gives reasons to claim that the Tsentralna mine (transformer 1) is characterized by an almost uniform supply of electricity and is independent of this production. Finally, you can allocate plots on 09/23/2021 from 3:00 p.m. to 11:00 p.m. and on 09/24/2021 from 11:00 p.m. to 9:00 a.m. the time intervals for 09.25 and 09.26 are similar.

For the Tsentralna mine (transformer 2), it should be noted the uniform supply of electricity (Fig. 1.10). Production has a jump-like character. A decrease in electricity supply and, accordingly, production is observed on 09/20/2021 from 3:00 p.m. to 10:00 p.m. and on 09/21/2021 from 11:00 p.m. to 6:00 a.m. In the future, it is possible to fix the visual lack of correlation between electricity supply and production.

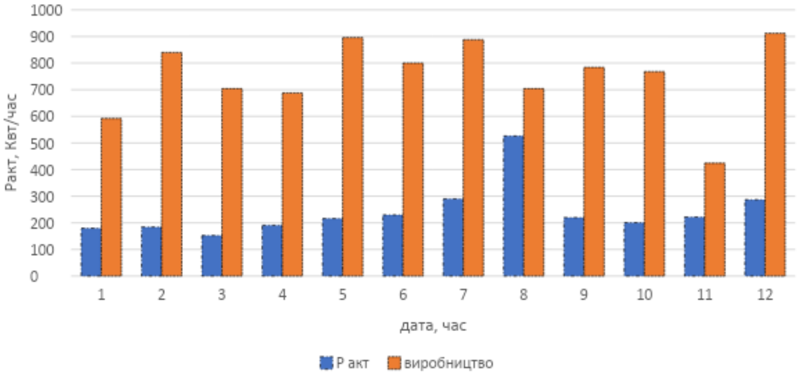

Figure 2.10 Monitoring of the power supply system - production for the Pokrovska mine in Kryvyi Rih

A visual analysis of the power supply-production system (Fig. 1.10) provides the following information: on October 29, 2011, there was a surge in power supply, but production decreased. On October 30, 2021, in the period from 3:00 p.m. to 10:00 p.m., production was sharply reduced with a uniform power supply.

The research carried out by the author gives grounds for asserting the absence of certain regularities in the energy supply - production complex. For each individual enterprise, namely a specific mine, the stochasticity of each component system is available. That is, the uniformity of electricity supply does not correspond to the uniformity of production. There is no apparent dependence on the hourly supply of electricity. This indicates a lack of effective management of the power supply-production complex and currently requires its improvement.

Thus, we can claim that the conducted monitoring and analysis of the power supply system - production is the basis for further research. It is expedient to use the obtained information component in quantitative analytical modeling in order to obtain relevant recommendations for effective management of the power supply - production complex.

Today, it is not enough to be limited only to the control of the level of electricity consumption - it is necessary to manage this process. At the same time, the control system should respond adaptively and preventively to the occurrence of relevant factors that irritate the technology of changes in the modes of operation of electric receivers, which for the conditions of iron ore enterprises are stationary installations.

The research results indicate the existence of many alternatives regarding approaches to increase the energy efficiency of mining enterprises. But in these studies, the approach was limited only to the level of selection of structures of power supply systems of underground mining enterprises. Therefore, taking into account the new temporary trends, the problem of the need to manage energy flows of mining enterprises was formed and considered in the work. At the same time, specific solutions were lacking in these studies. Deterioration of technological conditions with an increase in the depth of mining of iron ore raw materials puts the problem of the need to increase the energy efficiency of mining iron ore raw materials to a new level of search. This is additionally confirmed by the fact that the majority of known studies [4] were conducted for the conditions of mining iron ore raw materials at depths of up to 1000 m. Nowadays, these marks have already crossed the boundaries of 1500–2100 m. It is clear that the amount of electricity consumption at such depths, and therefore the level of influence on the general indicators of the production cost of iron ore raw materials has grown and will continue to grow. All this allows us to state that in modern conditions it is appropriate to evaluate the efficiency of electricity consumption of iron ore enterprises with an underground method of iron ore raw material extraction.

In practical terms, this will ensure the energy efficiency of iron ore enterprises with an underground method of extracting iron ore raw materials.

The main content of the analysis of the efficiency of electricity consumption of enterprises with an underground method of extraction of iron ore raw materials is the construction of stochastic models for time series of voltage in distribution mine networks in the time domain and the use of these models in applications. If time varies discreetly, then the time series is discrete. Observations of a discrete time series of voltage in distribution mine networks, made at time points $t_1, t_2, \ldots, t_i, \ldots, t_N$, can be denoted by $u(t_1), u(t_2), \ldots, u(t_i), \ldots, u(t_N)$. If the observations are made at a fixed time interval Δt and there are N consecutive values of the observations of the series, one can write $u_1, u_2, \ldots u_i, \ldots u_N$, denoting the observations made at equidistant moments of time $t_0 + \Delta t, t_0 + 2\Delta t, \dots, t_0 + i \cdot \Delta t, \dots, t_0 + N\Delta t$. In the following, the values of t_0 and Δt are not important, but if it is necessary to accurately determine the observations, then it is necessary to specify their values. If we take t_0 as the beginning of time counting, i.e. $t_0 = 0$, and Δt as a unit of time, i.e. $\Delta t = 1$, then ui can be considered as the voltage observation at the i th moment of time. Their mathematical models are usually used to describe the behavior of physical objects. If a model based on physical laws can be obtained, such a model would be deterministic. At the same time, in practice, even such a model is not completely deterministic, since a number of unaccounted factors may participate in it. For such objects, it is not possible to offer a deterministic model that allows accurate calculation of the future behavior of the object. Nevertheless, it is possible to propose a model that allows you to calculate the probability that some future value will lie in a certain interval. Such a model is called stochastic. Time series models of voltage in distribution mine networks in the time domain are actually stochastic. An important class of stochastic models for describing time series are stationary models. They are based on the assumption that the process remains in equilibrium with respect to a constant average level, which is confirmed by the study of time series of voltage in distribution mine networks in the time domain [5].

One of the important applied tasks is to predict the future values of a time series based on its current and past values. In practice, there is always a need to forecast ahead for an interval called the warning time. The main feature in the development of stochastic time series models is the assumption of stationarity. A stationary stochastic time series is conveniently described by its mean, variance, and autocorrelation function. To estimate the average value of a discrete stochastic process, you can use the sample average

$$\bar{u} = \frac{1}{N}\sum_{i=1}^{N} u_i \ , \tag{1.1}$$

where $u_1, u_2, \dots, u_N -$ time series values.

In turn, the variance of a discrete stochastic process is estimated using the sample variance

$$\sigma_u^2 = \frac{1}{N-1}\sum_{i=1}^{N} (u_i - \bar{u})^2 \ . \tag{1.2}$$

To estimate the relationship between the values of the time series, autocorrelation is used with a delay k, which is equal to

$$\rho_k = \frac{1}{(N-1)\cdot\sigma_u^2}\sum_{i=1}^{N-k} (u_i - \bar{u})(u_{i+k} - \bar{u}) \ , \qquad (1.3)$$

$$k = 0, 1, 2, \ldots, K \ .$$

When studying discrete stochastic processes, which are time series of voltage in distribution mine networks in the time domain, the problem of emissions arises [6]. The problem of emissions for the mentioned time series means determining the output of the ordinate of the random time series for a given level and finding the probabilistic characteristics of the time the ordinates of the random time series stay above the given level. It is clear that emissions have a negative effect on the efficiency of electricity consumption of enterprises with an underground method of mining iron ore raw materials. In particular, we will consider the definition of the probability of an emission for a given value of the argument of a random time series and the determination of the average number of emissions falling on a given time interval, as well as the average duration of an emission.

Let some number α be given, which determines the voltage level, for which emissions are related to the quality of electricity consumption. Let us denote the value of an element of a random time series at an arbitrary moment of time i by u_i. Then the sought probability of emission $p_i(\alpha)$ at moment of time i will be determined by the equality

$$p_i(\alpha) = P\{u_i \le \alpha; \alpha < u_{i+1}\} \ . \qquad (1.4)$$

To determine the probability (1.4), we consider the two-dimensional distribution density

$$f(u_i, u_{i+1}) \qquad (1.5)$$

ordinate of the random time series. Then the probability (1.4) can be represented in the form of an integral

$$p_i(\alpha) = \int_{-\infty}^{\alpha} \int_{\alpha}^{+\infty} f(u_i, u_{i+1}) du_{i+1} du_i \ . \qquad (1.6)$$

In a similar way, the emission possibility for level α can be calculated from top to bottom

$$\tilde{p}_i(\alpha) = P\{u_i \ge \alpha; \alpha > u_{i+1}\}. \qquad (1.7)$$

Then formula (2.7) taking into account (2.5) takes the form

$$\tilde{p}_i(\alpha) = \int_{\alpha}^{+\infty} \int_{-\infty}^{\alpha} f(u_i, u_{i+1}) du_{i+1} du_i \,. \tag{1.8}$$

In the case of a stationary stochastic time series, the two-dimensional distribution density (1.5) does not depend on the index i, therefore, probabilities (1.6) and (1.8) will have constant values for any value of time i.

In this case, formulas (1.6) and (1.8) will take the form, respectively

$$p(\alpha) = \int_{-\infty}^{\alpha} \int_{\alpha}^{+\infty} f(u_i, u_{i+1}) du_{i+1} du_i \,, \tag{1.9}$$

$$\tilde{p}(\alpha) = \int_{\alpha}^{+\infty} \int_{-\infty}^{\alpha} f(u_i, u_{i+1}) du_{i+1} du_i \,. \tag{1.10}$$

In practice, it often makes sense to consider a stochastic stationary normal time series with independent elements. Then for the two-dimensional density distribution (1.5) we will have [7]

$$f(u_i, u_{i+1}) = \frac{1}{2\pi\sigma^2} e^{-\frac{(u_i - \bar{u})^2 + (u_{i+1} - \bar{u})^2}{2\sigma^2}}, \tag{1.11}$$

where $\bar{u}$ is the average value of the voltage, V, and σ is the average square deviation of the voltage, V.

Substituting (1.11) into (1.9), we find the probability value

$$p(\alpha) = \frac{1}{2\pi\sigma^2} \int_{-\infty}^{\alpha} \int_{\alpha}^{+\infty} e^{-\frac{(u_i - \bar{u})^2 + (u_{i+1} - \bar{u})^2}{2\sigma^2}} du_i du_{i+1} \,, \tag{1.12}$$

We transform the integral (1.12), reducing it to the product of two integrals

$$p(\alpha) = \frac{1}{2\pi\sigma^2} \int_{-\infty}^{\alpha} e^{-\frac{(u_i - \bar{u})^2}{2\sigma^2}} du_i \int_{\alpha}^{+\infty} e^{-\frac{(u_{i+1} - \bar{u})^2}{2\sigma^2}} du_{i+1} \,. \tag{1.13}$$

To calculate integrals, it is convenient to present formula (1.13) in the form

$$p(\alpha) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\alpha} e^{-\frac{(u_i - \bar{u})^2}{2\sigma^2}} du_i \cdot \frac{1}{\sqrt{2\pi}\sigma} \int_{\alpha}^{+\infty} e^{-\frac{(u_{i+1} - \bar{u})^2}{2\sigma^2}} du_{i+1} \,. \tag{1.14}$$

We calculate the first of the integrals in the formula (1.14)

$$\frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{\alpha} e^{-\frac{(u_i-\bar{u})^2}{2\sigma^2}}du_i = \left| t=\frac{u_i-\bar{u}}{\sigma}\ u_i = t\cdot\sigma+\bar{u}\ u_i=-\infty\to t = -\infty\ u_i=\alpha\to t=\frac{\alpha-\bar{u}}{\sigma}\ \ du_i=\sigma\cdot dt\right| = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\frac{\alpha-\bar{u}}{\sigma}} e^{-\frac{t^2}{2}}dt, \tag{1.15}$$

$$\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\frac{\alpha-\bar{u}}{\sigma}} e^{-\frac{t^2}{2}}dt = \frac{1}{2}\Phi(t)|_{-\infty}^{\frac{\alpha-\bar{u}}{\sigma}} = \frac{1}{2}\left[1+\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]$$

where $\Phi(x) = \frac{2}{\sqrt{2\pi}}\int_{0}^{x} e^{-\frac{t^2}{2}}dt$ – integral Laplace function.

Similarly, the second integral in formula (1.14) is calculated

$$\frac{1}{\sqrt{2\pi}\sigma}\int_{\alpha}^{+\infty} e^{-\frac{(u_{i+1}-\bar{u})^2}{2\sigma^2}}du_{i+1} = \frac{1}{2}\Phi(t)|_{\frac{\alpha-\bar{u}}{\sigma}}^{+\infty} = \frac{1}{2}\left[\Phi(+\infty) - \Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right] = \frac{1}{2}\left[1-\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]. \tag{1.16}$$

Considering (1.15) and (1.16), formula (1.14) takes the form

$$p(\alpha) = \frac{1}{2}\left[1+\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]\cdot\frac{1}{2}\left[1-\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right],$$

or, according to the difference of squares formula,

$$p(\alpha) = \frac{1}{4}\left[1-\Phi^2\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]. \tag{1.17}$$

Let us investigate the function (1.17) at the extremum, taking advantage of the fact that the derivative at the extremum point is zero [8]

$$p'(\alpha) = \left[\frac{1}{4}\left[1-\Phi^2\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]\right]' = -\frac{1}{2\sigma}\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\Phi'\left(\frac{\alpha-\bar{u}}{\sigma}\right) = 0,$$

$$p'(\alpha)|\alpha=\bar{u} = -\frac{1}{2\sigma}\Phi\left(\frac{\bar{u}-\bar{u}}{\sigma}\right)\Phi'\left(\frac{\bar{u}-\bar{u}}{\sigma}\right) = -\frac{1}{2\sigma}\Phi(0)\Phi'(0) = 0.$$

because $\Phi(0) = 0$.

Thus, when $\alpha = \bar{u}$ the function (1.17) reaches an extremum. To determine the nature of the extremum, we use the sign of the second-order derivative of the function (1.17) at the extremum point. We calculate the second-order derivative of the function (1.17) as a derivative of the first-order derivative of this function

$$p^{\prime\prime}\left[-\frac{1}{2\sigma}\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\Phi'\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]'\frac{1}{2\sigma^2}\left[\left(\Phi'\left(\frac{\alpha-\bar{u}}{\sigma}\right)^2+\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\Phi''\left(\frac{\alpha-\bar{u}}{\sigma}\right)(\quad)\right)[\quad]\right], \tag{1.18}$$

$$p^{\bar{\prime}\prime}\frac{1}{2\sigma^2}\left[\left(\Phi'(0)^2+\Phi(0)\Phi''(0)()\right)[]\frac{1}{2\sigma^2}{}'(0)^2\right].$$

Because

$$\Phi'(x)=\left[\frac{2}{\sqrt{2\pi}}\int_0^x \quad e^{-\frac{t^2}{2}}dt\right]'=\frac{2}{\sqrt{2\pi}}e^{-\frac{x^2}{2}},$$

$$\Phi'(0)=\frac{2}{\sqrt{2\pi}},$$

then, according to (1.18), still have

$$p^{\bar{\prime}\prime}\frac{1\quad 4\quad 1}{2\sigma^2 2\pi\pi\sigma^2} \tag{1.19}$$

According to condition (1.19), the function (1.17) at $\alpha=\bar{u}$ reaches a maximum.

Let's find the value of this maximum by substituting $\alpha=\bar{u}$ in the formula (1.17),

$$p(\bar{u})=\frac{1}{4}\left[1-\Phi^2\left(\frac{\bar{u}-\bar{u}}{\sigma}\right)\right]=\frac{1}{4}\left(1-\Phi^2(0)\right)=0.25\,. \tag{1.20}$$

Formula (1.20) indicates that the greatest probability of an outlier is reached when the outlier level line is equal to the sample mean.

Similarly, there is a formula for the probability of crossing level α from top to bottom, which has the form

$$\tilde{p}(\alpha)=\frac{1}{2}\left[1-\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]\cdot\frac{1}{2}\left[1+\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right],$$

or

$$\tilde{p}(\alpha)=\frac{1}{4}\left[1-\Phi^2\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right] \tag{1.21}$$

Thus, comparing formulas (1.17) and (1.21), we can conclude that the probabilities of crossing level α coincide. It is clear, if we consider emissions to both sides of the line of level α, then the probabilities (1.17) and (1.21) need to be added, i.e. doubled

$$\hat{p}(\alpha)=p(\alpha)+\tilde{p}(\alpha), \hat{p}(\alpha)=\frac{1}{2}\left[1-\Phi^2\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]. \tag{1.22}$$

To find the average time of stay of the stochastic time series above the level α calculated for the time interval T, we will have

$$\bar{t}_\alpha = T \cdot \int_\alpha^{+\infty} f(u_i) du_i \ , \tag{1.23}$$

or, given that

$$f(u_i) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(u_i - \bar{u})^2}{2\sigma^2}} \ , \tag{1.24}$$

formula (1.18) takes the form

$$\begin{aligned} \bar{t}_\alpha = T \cdot \int_\alpha^{+\infty} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(u_i - \bar{u})^2}{2\sigma^2}} du_i \\ = \frac{T}{\sqrt{2\pi}\sigma} \int_\alpha^{+\infty} e^{-\frac{(u_i - \bar{u})^2}{2\sigma^2}} du_i = \\ = \frac{T}{2}\left(1 - \Phi\left(\frac{\alpha - \bar{u}}{\sigma}\right)\right) \ , \bar{t}_\alpha \\ = \frac{T}{2}\left(1 - \Phi\left(\frac{\alpha - \bar{u}}{\sigma}\right)\right) \end{aligned} \tag{1.25}$$

Usually, the average time of stay of a stochastic time series above a given level α during one emission is of interest. To determine this average time $\bar{\tau}$, it is necessary to divide time $\bar{t}_\alpha$ by the average number of emissions $\bar{n}_\alpha$ that occurred during time T . To determine $\bar{n}_\alpha$, we divide the interval T into m equal intervals Δt_j and introduce auxiliary random variables N_j, each of which is equal to one if there is an outlier inside the interval and zero otherwise.

Then the total amount of emissions N_α during the interval T will be equal to the sum of the values N_j

$$N_\alpha = \sum_{j=1}^{m} N_j \ . \tag{1.26}$$

We find the mathematical expectation from both parts of equality (1.26)

$$M[N_\alpha] = \sum_{j=1}^{m} M[N_j] \ . \tag{1.27}$$

Considering that

$$M\left[N_\alpha\right]=\overline{n}_\alpha \quad \text{i} \quad M\left[N_j\right]=p(\alpha)\cdot\Delta t_j ,$$

we have, according to (1.27),

$$\overline{n}_\alpha=\sum_{j=1}^{m}p(\alpha)\cdot\Delta t_j=p(\alpha)\sum_{j=1}^{m}\Delta t_j=p(\alpha)\cdot T$$

$$\overline{n}_\alpha=p(\alpha)\cdot T \quad (1.28)$$

Considering (1.17), formula (1.23) takes the form

$$\bar{n}_\alpha=\frac{T}{4}\left[1-\Phi^2\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right] \quad (1.29)$$

Then the average duration of the stochastic time series above the given level α is found by the formula

$$\bar{\tau}=\frac{\bar{t}_\alpha}{\bar{n}_\alpha} . \quad (1.30)$$

According to (1.20) and (1.24), formula (1.30) takes the form

$$\bar{\tau}=\frac{\frac{T}{2}\left(1-\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right)}{\frac{T}{4}\cdot\left[1-\Phi^2\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]}=\frac{2}{\left[1+\Phi\left(\frac{\alpha-\bar{u}}{\sigma}\right)\right]} . \quad (1.31)$$

On the basis of theoretical study, the author carried out calculation studies of electricity consumption based on experimental data of the Kazatska mine, gor 1300.

In the table 1.4 provides statistical data on voltage for the period from 06/30/2021 to 07/06/2021.

Table 1.4

Statistical data on the voltage of Kazatska mine, gor 1300

№	High-voltage, u_k	№	High-voltage, u_k
1	6742	21	1051
2	2197	22	1478
3	1331	23	3033
4	1006	24	9080
5	7133	25	6743
6	9284	26	2585
7	2837	27	1331
8	9080	28	1024

№	High-voltage, u_k	№	High-voltage, u_k
9	6742	29	7219
10	2483	30	3811
11	1331	31	3033
12	1022	32	9080
13	3415	33	6744
14	1685	34	2590
15	2837	35	1331
16	9080	36	1024
17	6742	37	2563
18	2488	38	7714
19	1331	39	3040
20	1022	40	9080

The analysis of the time series allows us to draw a conclusion about the discreteness of the stochastic series. Let's find the numerical characteristics of this series. We find the sample mean according to formula (1.1)

$$\bar{u} = \frac{1}{40}\sum_{k=1}^{40} u_k = 4084 \tag{1.32}$$

The sample variance is found by formula (1.2)

$$\sigma_u^2 = \frac{1}{39}\sum_{k=1}^{40}(u_k - \bar{u})^2 = 8935149 \tag{1.33}$$

In turn, the standard deviation is equal to

$$\sigma_u = 2989 \tag{1.34}$$

To evaluate the connection between the members of the series from the table. 1.4 we will use autocorrelation with delay k according to formula (1.3)

$$\rho_k = 2.87 \cdot 10^{-9} \sum_{i=1}^{40-k} (u_i - 4084)(u_{i+k} - 4084) \text{ .., } \tag{1.35}$$

($k = 0, 1, 2, 3, 4$).

The next issue is the analysis of voltage deviations, which can be interpreted as emissions. Given that there is no connection between the members of a discrete stochastic series and assuming that the stochastic series is normal, we calculate the probability that the voltage output will exceed a given level.

The calculation was carried out according to the formula (1.17)

$$p(\alpha) = \frac{1}{4}\left[1 - \Phi^2\left(\frac{\alpha - 4084}{2989}\right)\right]. \qquad (1.36)$$

The results of calculations according to formula (1.36) are presented in table 1.5

Table 1.5

Calculations of the probability of voltage exceeding a given level

α, в	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
p	0.079	0.128	0.184	0.23	0.25	0.236	0.193	0.138	0.086	0.048	0.023

According to calculations, the probability of an outlier first increases, reaching its greatest value when the outlier level is equal to the sample mean, i.e

$$\alpha = \overline{u}\ . \qquad (1.37)$$

To find the average time of stay of the stochastic time series above the level α calculated for the time interval T, we use the formula (1.25)

$$\bar{t}_\alpha = \frac{T}{2}\left(1 - \Phi\left(\frac{\alpha - 4084}{2989}\right)\right). \qquad (1.38)$$

For the convenience of further calculations, we present formula (1.38) in the form

$$\tilde{t}_\alpha = \frac{\bar{t}_\alpha}{T} = \frac{1}{2}\left[1 - \Phi\left(\frac{\alpha - 4084}{2989}\right)\right]. \qquad (1.39)$$

The results of calculations according to formula (1.39) are presented in the table. 1.5

Table 1.5

The results of calculating the average stay time of the stochastic time series above level α

α, в	0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
$\acute{t}_\alpha$	0.914	0.849	0.757	0.642	0.511	0.38	0.261	0.165	0.095	0.05	0.024

The analysis of the given results shows that as the emission level α increases, the average time of the stochastic time series above the level α per unit time interval T decreases.

The analysis of the given results shows that the average duration of the stochastic time series above the given level of α decreases with the increase in the emission level α .

Thus, the conducted research made it possible to reach the following conclusions, namely: it was established that in modern conditions of mining of iron ore raw materials by the underground method associated with the further deepening of mines, a more thorough analysis of power consumption by various devices is necessary, in particular, an analysis of voltage emissions in the nominal mode.

Based on the real operating conditions of iron ore enterprises, a mathematical model was built that allows to study the quality of electricity consumption. The peculiarity of the proposed mathematical model is that it allows the analysis of the impact of voltage emissions for a given nominal level. The study of emissions of stochastic time series of voltage in the mine network makes it possible to meet the requirements for energy efficiency in underground developments.

1.3. Systematic evaluation of energy-efficient modes of electricity supply

Decisions in science, design and technical operation of equipment must be made quickly with minimal risk of errors. This is facilitated by a systematic analysis, a systematic approach when solving specific scientific, project and other technical tasks. System analysis refers to the directions of modern science of management, which arose in the period of aggravation of technical problems, which caused the need to find and justify new solutions.

There are a considerable number of conflicting terms for the term "system". In the encyclopedia, this term is interpreted as follows: "System (from the Greek sustema - a whole consisting of parts; a connection) - a set of elements that, in relations and connections with each other, form a certain integrity, unity."

System analysis is a set of means of scientific knowledge and applied research used to prepare and substantiate decisions regarding complex problems of a scientific nature. In system analysis under conditions of uncertainty and stochasticity.

In system analysis, methodology, hardware implementation, and practical programs are distinguished. The rapid growth of technical progress posed challenges for the solution of which scientific methods were involved and developed.

Engineering is related to complex systems, which are characterized by numerous and diverse types of connections between separately existing elements of the system and the presence of a function of purpose in the system, which is not present in its constituent parts.

Naturally, system analysis is a set of processes and procedures. That is, studying power supply systems, we can note that a complex system is a system that consists of elements of different types and has heterogeneous connections between them. Taking into account the current state and development of power supply systems and automation of the control process, we note that the analyzed system is a complex system with the determining role of two elements: technical means and human actions. To study the system, it is necessary to carry out decomposition or synthesis of the system, that is, to determine the structure of the system. The structure of the system is the division of the system into groups of elements with an indication of the connections between them, which is constant for the entire time of consideration and gives an idea of the system as a whole. Distribution can have a material, functional, algorithmic and other basis.

System analysis examines both the organization of such sets and the type of individual procedures that are optimally adapted for making management decisions in a complex system.

System analysis examines both the organization of such sets and the type of individual procedures that are optimally adapted for making management decisions in a complex system.

Separate procedures (operations) are usually classified into formalized and informalized. System analysis suggests that in certain situations informal decisions made by humans are better.

Environment. The concept of "system" implies a boundary between something limited by a set of elements. The elements remaining outside the boundary form a set called the external environment. Any system can be considered, on the one hand, as a subsystem of a higher order (supersystem), and on the other hand, as a supersystem of a lower order system.

The study of such a complex technical system as the power supply of underground mining enterprises involves the definition of the main author's concepts, which we will rely on in the research process. Thus, functionality is a manifestation of individual properties (functions) of the system in interaction with the external environment. The structure of the system is the way the system exists and expresses its function. Integrity is an expression of the internal unity of the object, the presence of all the necessary elements with connections between them, the relative autonomy of the object in the sense of independence from the environment. Connections are elements that carry out direct interaction between elements (or subsystems) of the system, as well as with elements and subsystems of the environment. Connections are distinguished by the nature of the relationship (direct and reverse) and by the type of manifestation (deterministic and probabilistic). Criteria are signs that are used to assess the compliance of the system's functioning with the desired result (goals) under the given restrictions. The efficiency of the system is the ratio between the specified indicator of the result of the functioning of the system and the actual one.

The technical system has a stably expressed target function. There are simple technical systems in which efficiency is maintained by regulating processes, and complex systems in which efficiency is maintained by parameter regulation. Functionally, the technical system consists of three blocks: input – process – output.

In our opinion, in order to format the logistics of the research of the analyzed problem, it is appropriate to single out three components as a system element: 1) at the entrance - checking the resources necessary for the implementation of the program of effective activity of the research object; 2) process – verification of program execution (in the course, it is possible, for example, to determine whether real processes correspond to the previously developed plan, development of the forecast); 3) at the output - checking the results of the program.

The scheme of mutual influence of the external and internal environment is shown in fig. 1.11.

Input is everything that changes during the course of the process (functioning of the system).

Output is the result of the final state of the process.

The process is the transition of input into output.

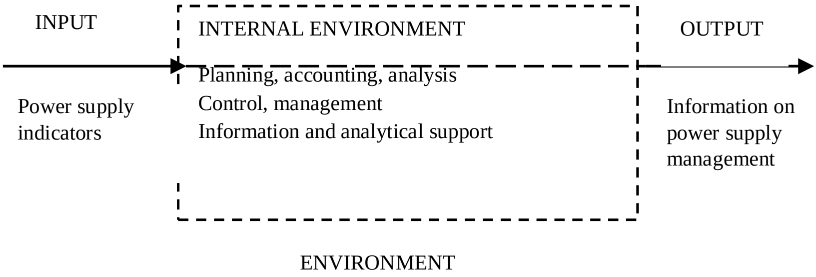

Figure 1.11 Component systems of electricity supply and electricity consumption in interaction with the environment

The input and output are located at the system boundary and simultaneously perform the input and output functions of previous and subsequent systems.

The definition of the functioning of the system is related to the concept of a "problem situation", which occurs if there are differences between the required (desired) and the existing (real) input. The problem is the difference between the existing and desired systems. If there is no problem, then there is no problem. To solve the problem means adjusting the old system or constructing a new, desirable.

Between the components of the set forming the system, there are system-forming connections and relations, thanks to which the system-specific unity is realized.

Relationships differ from connections in that they do not have a pronounced material-energy character. However, their accounting is important for understanding one or another system. Relations can be spatial, temporal), quantitative.

States and phases of functioning are important for the analysis of systems operating over a long period of time. The very process of functioning is known by identifying connections and relationships between different states.

Any system exists only within certain limits of changes in its properties, therefore maximum and minimum values of its variables are usually set. A complex system is the result of the evolution of a simpler system. The system can be studied, and even its genesis can be studied.

The progressive development of the system is accompanied by qualitative leaps. Therefore, the progress of the system is accompanied not only by the quantitative growth of parameters, but also by a change in its quality. This allows the consideration of qualitative information criteria for development.

Progressive development is always associated with limiting diversity. Of the many possible scenarios of evolution, only one is realized in practice. But this process is accompanied by an increase in the complexity and internal diversity of progressive systems. Therefore, any process of information movement is associated with destruction, limitation of one type of diversity and simultaneous increase of another type. Intrinsic properties depend only on connections (interactions) within the system, they are properties of the system "in itself". External properties actually exist only when there are connections, interactions with external objects (systems). Connections of the studied object can also be components in its system analysis. Connections have a substance-energy nature.

Scientists, taking into account personal experience, develop "their own system". But using a system approach allows you to quickly understand and choose the optimal methods for your activity.

It goes without saying that improving the power supply system is a very time-consuming and responsible process. To find one successful technical solution, it is necessary to work out more than fifty technical ideas. Reducing time and labor costs for improving the quality indicators of the power supply system is ensured, in particular, by the use of forecasting methods and optimization of technical solutions.

The systematic approach to the improvement of the power supply system consists in substantiating the laws, basic principles and trends of development, in accounting for qualitative and quantitative indicators, rational organization of technical and technological operation.

At the stage of scientific research, in some cases, the search for a rational principle is conducted, in others, the search for the direction of improving characteristics, in others, the study of the possibility of using future designs produced by industry, in the fourth cases, the suitability of certain inventions is checked.

Forecasts are developed for the period during which the adopted decision will have an effective effect. At the same time, electricity supply forecasting should be linked to the general forecast that characterizes the development of the mining industry. For forecasting, you need to know the historical laws of technology development and the factors that determine this development. Factors determining the development of technology are divided into external and internal.

External factors represent the need for the development of power supply systems, which determine the prerequisites and conditions, the pace of development. They are divided into needs, opportunities and limitations.

The needs are divided into the needs of the mining industry in general, the needs of a specific field of use of the production process. The needs of industry are expressed in the fact that the power supply should ensure increased labor productivity, optimization of the use of energy resources. The needs of the production process are the needs of the implementation of certain rational technological processes.

Another group of external factors is the scientific and technical, production capabilities of the industry to realize directions of energy efficiency development, which are determined by the needs of electricity supply. Scientific and technical capabilities are determined by the level of science, technology, and technology achieved at the time when the implementation of the relevant areas of energy efficiency development will be necessary.

The rate of development of technology is largely determined by the level of development of science. Today, science has become a leading link in the "science - technology - production" system. The period from the discovery (idea, formulation of a new technical principle) to its practical implementation has been significantly shortened. For example, the idea of an internal combustion engine was proposed by F. Lebon in 1801, and the first internal combustion engine, designed by N. Otto and which received practical application, appeared only in 1878, i.e. the lag (gap in time) was almost 80 years. Currently, this lag is 10-15 years or less for equipment.

In any case, for the practical implementation of an idea, there must be a scientific justification of the possibilities of its implementation. Production capabilities are characterized by compliance with the technical level of the enterprise, the level of qualification of its employees and the level of production capacity.

External factors can speed up or slow down the development of technology, change development trends.

Such factors as the duration of research and development periods also affect the rate of development. works, preparation of production, preceding the industrial development of the latest technologies, introduction into the field of application.

Internal factors are inherent in the power supply system itself. An important factor is the natural laws on which the technical principle is based.

Another important internal factor is the length of the life cycle of the technical principle on which the power supply system is based and the degree of utilization of its potential at the time of forecasting. In the stage of mastering the technical principle, the development of the system proceeds at an accelerated pace, but then the pace of development slows down and, finally, the development stops: the technical principle has exhausted itself.

The third factor that determines the pace and trends of the development of the system, especially in the early stages, is the conformity of the constructive form used with the content of the technical principle. There is a certain continuity of the form of the power supply system of the same functional purpose, but based on different technical principles. If the form corresponds to the new principle, it contributes to the acceleration of the pace of development, if not, then the pace of development slows down.

Internal factors reflect internal technical contradictions, the solution of which is the driving force behind the development of types and types of electricity supply. This reveals the effect of the law of unity and the struggle of opposites, which determines the internal logic of the system's development. It is possible to single out fundamental and constructive contradictions in the development of technology.

Principle contradictions can be characterized as a discrepancy between the technical principle used in the power supply system and the required functional properties. Solving this contradiction means changing the technical principle.

In fig. 1.12. the factors determining the development of the power supply system of industrial enterprises are shown.

The modern stage of development of technical systems involves the use of work automation, which consists in the use of CAD (automatic design systems) and other software tools. Optimization design involves choosing the best of all possible solutions. Resource design consists in determining the resource of all components of the power supply in accordance with the accepted regulatory resource. Resource design in terms of labor intensity can be compared with the development of design documentation and is currently in its nascent stage. Mathematical modeling is used in optimization and resource design. Narps use typification and complexity. Typing consists in the fact that types with specific parameters and dimensions are developed for production. Type means a technically and economically justified set of types and standard sizes that have a common purpose. Typical technical systems are based on a basic model, which is understood as a constructive implementation, which is the basis for a number of similar types or its modifications. Complexity consists in the development of a set of components of the technical system for the performance of all technological operations, coordinated by performance and other characteristics. Complexity is the basis of creating automated systems.

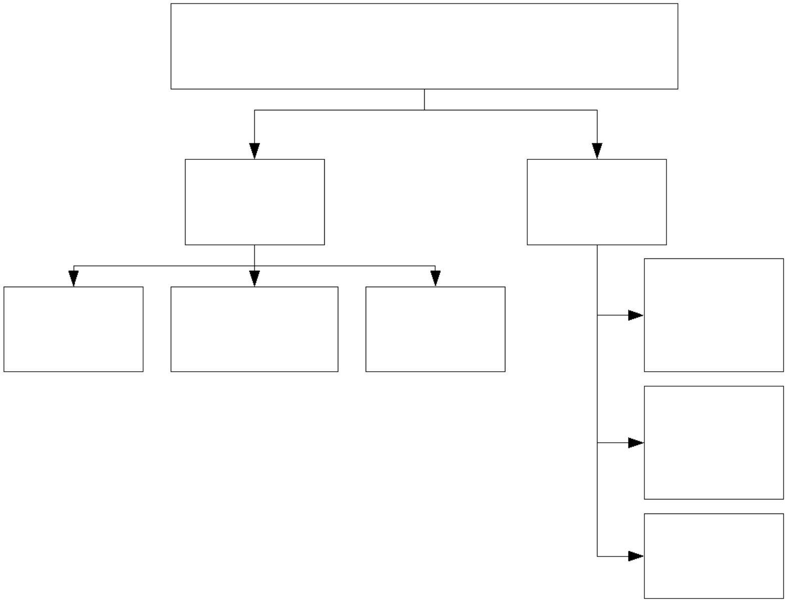

Figure 1.12 Factors of the development of electricity supply and electricity consumption systems of mining enterprises at the current level of their systematicity

The author proposed to investigate the system of evaluating the process of electric energy consumption, highlighting the hierarchy of the controlled system with subsystems of the production-executive structure and the production-technological one (Fig. 2. 13). The formed three-level hierarchy will allow to highlight the latent synergistic effects inherent in complex technical systems.

Undoubtedly, the systemic approach involves the formation and application of a set of principles that are inherent in the system under study. In our opinion, it is advisable to propose the following system of principles for the power supply system. The principle of hierarchy consists in distributed power supply systems into component units consisting of component units of the first level, units of the second level and subsequent levels, control and management systems, and systems that support the operation of the technical system.

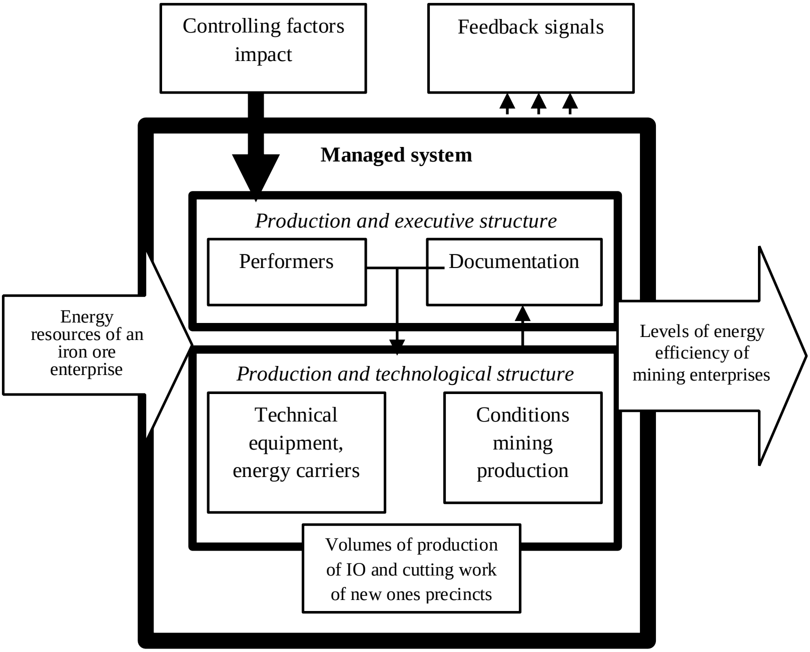

Figure 1.13 Generalized structure of the system for evaluating the process of electric energy consumption of an iron ore enterprise

The principle of decomposition (blocks, modular principle) allows independent parallel formation of separate constituent units, their verification, transfer to general formation in a finished form. This principle makes it possible to implement the block method.

To ensure the modular principle, the system must have a clear division into component units, a high compatibility factor, which is equal to

$$К_с = \frac{К_ч}{К_з} \qquad (1.40)$$

where $К_с$ is the compatibility coefficient; $К_ч$ - indicators characterizing parts of the system; $К_з$ general values of indicators characterizing the system in general.

Unification and standardization consist in the use of unified or standard components in power supply systems.

Standard includes the main parameters set by state, industry standards, as well as norms. Enterprise standards used in production belong to unified standards.

Unification and standardization eliminate unnecessary diversity, make system operation cheaper.

The level of standardization and unification is assessed by the coefficients of application of standard Кст or unified Ку component parts determined by formulas

$$К_{ст} = \frac{н_{ст}}{н_{ст} + н_у + н_о} 100\% \qquad (1.41)$$

$$К_у = \frac{н_у}{н_{ст} + н_у + н_о} 100\% \qquad (1.42)$$

where $К_{ст}$ is the standardization coefficient; $К_у$ is the unification coefficient; $н_{ст}$, $н_у$, $н_о$ - respectively, the number of standard, unified and original component parts.

It is natural that currently qualitative indicators are used in addition to quantitative indicators. Qualitative indicators determine the set of properties that determine the suitability to meet certain needs according to the purpose.

The most important group of technical system quality indicators are reliability indicators. Reliability indicators - characterize the ability of the technical system to perform the specified functions at the present time or within the specified time period, to maintain operational indicators over time within the specified limits, corresponding to the specified solutions and conditions of use.

The main indicators of reliability are reliability, durability, maintainability, preservation, as well as controllability.

Reliability is the property of maintaining operational efficiency during a period of operation without forced interruptions (failures). It is characterized by the probability of failure-free operation, failure recovery, warranty recovery.

Durability is the ability to maintain performance up to the limit state with the necessary breaks for maintenance and repair. It is characterized by the following categories: resource, service life between repairs, service life before the first overhaul, etc.

Repairability – adaptability to the prevention, detection and elimination of failures through maintenance and repair. Maintainability can include controllability, which means adaptability to control and diagnose the technical condition during operation. Preservation - preservation of operational indicators during and after the period of storage and transportation established by the technical documentation.

An important indicator of the reliability of large technical systems is the redundancy of individual components.

In our opinion, the quality of complex technical systems is the technical core of competitiveness, which is also determined by their cost, as well as energy intensity, that is, the cost of electricity per unit of products produced.

If the component qualities are expressed respectively in relative or absolute values. The integral quality indicator characterizes the choice of the best (from the economic and technical point of view) option of the power supply system. This indicator is extremely important when choosing one or another direction of technical development, creation of new systems, since only a combination of technical and economic evaluations gives an idea of the feasibility of the decision made.

I single out a separate component of the modern development of science - system engineering. In our opinion, it is appropriate to consider system engineering as a modern component of system analysis. In general, systems engineering is a special activity for the creation of complex technical systems, and in this sense it is primarily a modern type of engineering, technical activity, but at the same time it includes a special scientific activity, since it also involves the production of new knowledge. Thus, in systems engineering, scientific knowledge goes through a full cycle of functioning - from its acquisition to its use in engineering practice. System engineering solves two main system engineering tasks: integration of parts of a complex system into a single whole and management of the process of creating this system. System engineering is a product of the development of traditional engineering and design, but a qualitatively new stage associated with the growing complexity of designed technical systems.

SECTION 2.

MODELING OF POWER SUPPLY SYSTEM - ELECTROSPRODUCTION – PRODUCTION AT IRON ORE ENTERPRISES

2.1 Research of electrical consumption as a stochastic process under conditions of iron ore raw material production

The capitalization of relations in Ukraine requires a more careful approach to the extraction of minerals. When mining iron ore, optimal power consumption is of great importance, which allows to ensure the necessary working conditions, especially from the point of view of energy saving. As a result, in modern conditions, digital monitoring of electricity consumption is of great importance. The method of calculating electricity consumption, which is currently used, has insufficient accuracy, since the calculations are carried out on average values, without taking into account the stochasticity of the processes. Taking stochasticity into account through mathematical modeling of electricity consumption with the use of IT technologies makes it possible to improve the calculation of its characteristics during iron ore mining. As an example, the mathematical modeling of electricity consumption at the mine of the Kryvyi Rih iron ore basin is considered.

The analysis of publications shows that in order to increase the production of iron ore, it is necessary to carefully consider the peculiarities of electricity consumption [1]. In recent years, enterprises of the iron ore industry of Ukraine have been experiencing a process of falling productivity, which is primarily related to the complication of the conditions for the extraction of iron ore underground [2]. Solving issues related to the decline in iron ore production can be achieved by developing digital methods of monitoring electricity consumption based on the use of modern IT technologies. This process is complicated by the fact that nowadays the methods of calculating the properties of electricity consumption during the production of iron ore are outdated and far from perfect [3]. There is an invigoration of activities aimed at eliminating negative points in the methods of assessing the properties of electricity consumption during iron ore extraction in Ukraine [4]. At the same time, there are shortcomings that are associated with the peculiarities of taking into account the characteristics of electricity consumption during iron ore extraction. This is especially the case with such electricity consumption, which has a stochastic character. It is clear that the assessment of the characteristics of electricity consumption, according to the old methods, based on average indicators does not meet the modern requirements for the quality of calculations and requires new approaches.

As one of the possible approaches, we propose mathematical modeling of electricity consumption during the production of iron raw materials as a stochastic process in order to take into account its features. In the course of this study, the stochasticity of the process of electricity consumption during the production of iron ore raw materials is taken into account with the assessment of its properties.

The production of iron ore, especially by the underground method, necessitates the use of intensive electricity consumption. It should be emphasized that electricity consumption is quite significant in the total costs of producing iron ore raw materials. As a result, it is of great importance to track electricity consumption in digital form, which can be carried out by means of mathematical modeling in the presence of wide application of IT technologies [5].

In real conditions, the power consumption at the enterprise is a stochastic function, as it is caused by various previously unknown reasons at each moment of time. Next, we will assume that the power consumption $W(t)$ is a stationary random process in the broad sense, that is, its mathematical expectation is constant, and the correlation function depends only on the difference of arguments [6]

$$M[W(t)] = m_w = const, K_w(t_1, t_2) = K_w\,(\tau), \qquad (2.1)$$

where $\tau = t_2 - t_1$.

Formulas (2.1) allow you to take into account the stochastic nature of the change in power consumption. Thus, to characterize power consumption as a stochastic process within the framework of the correlation theory, it is necessary to know not only its average value, but also the correlation function and variance.

In practice, questions arise related to the need to calculate the amount of electricity consumption for a given period of time, that is, the calculation of the integral of the power consumption as a stochastic function

$$Q(T) = \int_0^T W(t)dt, \qquad (2.2)$$

where $[0; T]$ is the specified time interval of electricity consumption, h.

The mathematical expectation of the function (1.2) is found by the formula

$$M[Q(T)] = M\left[\int_0^T W(t)dt\right] = \int_0^T M[W(t)]dt = \int_0^T m_w dt = m_w \cdot T,$$

i.e

$$m_q(T) = m_w \cdot T. \tag{2.3}$$

Considering that the function under the integral sign (2.2) is stationary, the correlation function of the integral (2.2) will be written in the form of a double integral

$$K_q(t_1, t_2) = \int_0^{t_1} \int_0^{t_2} K_w(t'' - t')dt'dt''. \tag{2.4}$$

Since the expression on the right in formula (2.4) depends separately on the arguments and not on their difference, the integral of the stationary process does not have the property of stationarity. However, due to the stationarity of $W(t)$, formula (2.4) can be represented as a linear combination of definite integrals

$$K_q(t_1, t_2) = \int_0^{t_2} (t_2 - \tau)K_w(\tau)d\tau + \int_0^{t_1} (t_1 - \tau)K_w(-\tau)d\tau - \int_0^{t_2 - t_1} (t_2 - t_1 - \tau)K_w(\tau)d\tau \tag{2.5}$$

If in formula (2.5) we assume that $t_2 = t_1 = T$, then for the variance of the integral (2.2) we get an expression that depends on the parameter T, which shows the non-stationarity of the integral from the stationary function [7]

$$D[Q(T)] = 2\int_0^T (T - \tau) \cdot K_w(\tau)d\tau, \tag{2.6}$$

and the root mean square deviation taking into account (2.6) will be determined by the formula

$$\sigma[Q(T)] = \sqrt{2} \cdot \sqrt{\int_0^T (T - \tau)K_w(\tau)d\tau}\,. \tag{2.7}$$

The research of electricity consumption as a stochastic process allows solving the "emission problem", that is, the intersection of a random function of a given level. This allows, in particular, to determine the average time during which the power consumption will exceed a given level due to random fluctuations in the power consumption. It is clear that such an excess of power consumption has a negative effect on the economic performance of the enterprise.

If a stationary stochastic process is considered, then the average duration of the emission has obvious significance. For stationary processes, the density of the distribution of power consumption values and the density of the distribution of values and speed of power consumption do not depend on time, so the formulas for the average time of a stationary random function above a given level $w = w_o$ during time T, the average number of emissions during this time interval and the average duration emission will take the form [8]

$$\bar{t}_{w_0} = T \int_{w_0}^{\infty} f_1(x)dx, \tag{2.8}$$

$$\bar{n}_{w_0} = T \int_{0}^{\infty} v \cdot f_2(w_0, v)dv, \tag{2.9}$$

$$\bar{\tau} = \frac{\int_{w_0}^{\infty} f_1(x)dx}{\int_{0}^{\infty} v \cdot f_2(w_0, v)dv}, \tag{2.10}$$

where $f_1(w) -$ density distribution of power consumption values, $f_2(w, v) -$ two-dimensional density distribution of power consumption values and the rate of change of power consumption.

For a stationary process, it is advisable to introduce the concept of the average number of emissions per unit of time

$$\bar{v}_{w_0} = \int_{0}^{\infty} v \cdot f_2(w_0, v)dv, \tag{2.11}$$

i.e. is equal to the probability of emission per unit of time.

Moreover, if the power consumption $W(t)$ is a normal random function, then the integral (2.2) will also be a normal process, which can be fully characterized by its mathematical expectation (2.3) and mean squared deviation (2.7).

For a normal steady-state power consumption process, the distribution law of random function values is expressed through the mathematical expectation m_w and its dispersion

$$\sigma_w^2 = K_w(0),$$

because

$$f_1(w) = \frac{1}{\sigma_W \sqrt{2\pi}} e^{-\frac{(w - m_W)^2}{2 \cdot \sigma_W^2}}. \tag{2.12}$$

The rate of change of power consumption and the value of power consumption are independent random variables for a normal random process. Therefore, the two-dimensional density of the distribution of values and the rate of change of power consumption decomposes into the product of the normal densities of values and the rate of change of power consumption

$$f_2(w, v) = \frac{1}{\sigma_W \sqrt{2\pi}} e^{-\frac{(w - m_W)^2}{2 \cdot \sigma_W^2}} \cdot \frac{1}{\sigma_V \sqrt{2\pi}} e^{-\frac{v^2}{2 \cdot \sigma_V^2}}. \tag{2.13}$$

The dispersion of the rate of change m_w is equal to the value of the correlation function of power consumption at zero, i.e

$$\sigma_v^2 = -\frac{d^2}{d\tau^2} K_w(0), \qquad (2.14)$$

and the mathematical expectation due to the stationarity of the random process is zero

$$M[V(t)] = m_v = 0.$$

Taking into account (1.12) according to formula (1.8), we consistently obtain the formula for the average time a normal stationary random function stays above the given level $w = w_o$ during the time T.

$$\bar{t}_{w_0} = \frac{T}{\sigma_w\sqrt{2\pi}} \int_{w_0}^{\infty} e^{-\frac{(w-m_w)^2}{2\sigma_w^2}} dw$$

$$= \left| t = \frac{w - m_w}{\sigma_w} \; dw = \sigma_w dt \; w = w_0 \Rightarrow t = \frac{w_0 - m_w}{\sigma_w} \; w \right.$$

$$\left. = \infty \Rightarrow t = \infty \right| = \frac{T}{\sqrt{2\pi}} \int_{\frac{w_0 - m_w}{\sigma_w}}^{\infty} e^{-\frac{t^2}{2}} dt =$$

$$= -\frac{T}{\sqrt{2\pi}} \int_{\infty}^{\frac{w_0 - m_w}{\sigma_w}} e^{-\frac{t^2}{2}} dt$$

$$= \frac{T}{2}\left[\frac{2}{\sqrt{2\pi}} \int_0^{\infty} e^{-\frac{t^2}{2}} dt - \frac{2}{\sqrt{2\pi}} \int_0^{\frac{w_0 - m_w}{\sigma_w}} e^{-\frac{t^2}{2}} dt\right]$$

$$= \frac{T}{2}\left[1 - \Phi\left(\frac{w_0 - m_w}{\sigma_w}\right)\right],$$

$$\bar{t}_{w_0} = \frac{T}{2}\left[1 - \Phi\left(\frac{w_0 - m_w}{\sigma_w}\right)\right], \qquad (2.15)$$

where $\Phi(x) = \frac{2}{\sqrt{2\pi}} \int_0^x e^{-\frac{t^2}{2}} dt$ – integral Laplace function.

Next, we find, according to formula (2.9), the average number of emissions of a normal stationary random function above the given level $w = w_o$ during time T

$$\bar{n}_{w_0} = \frac{T}{\sigma_w\sqrt{2\pi}} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}} \int_0^\infty v\cdot\frac{1}{\sigma_v\sqrt{2\pi}} e^{-\frac{v^2}{2\cdot\sigma_v^2}} dv$$

$$= \left| t = \frac{v^2}{2\sigma_v^2}\ vdv = \sigma_v^2 dt\ v = 0 \Rightarrow t = 0\ v = \infty \Rightarrow t \right.$$

$$\left. = \infty \right| == \frac{T}{\sigma_w\sqrt{2\pi}} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}} \int_0^\infty \frac{\sigma_v}{\sqrt{2\pi}} e^{-t} dt$$

$$= \frac{T\sigma_v}{2\pi\sigma_w} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}} \int_0^\infty e^{-t} dt$$

$$\bar{n}_{w_0} = \frac{T\sigma_v}{2\pi\sigma_w} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}}. \qquad (2.16)$$

In turn, the formula for the average duration of the emission of a normal stationary random function above the given level $w = w_o$ according to (2.15) and (2.16) will take the form

$$\bar{\tau} = \frac{\bar{t}_{w_0}}{\bar{n}_{w_0}} = \frac{\frac{T}{2}\left[1-\Phi\left(\frac{w_0-m_w}{\sigma_w}\right)\right]}{\frac{T\sigma_v}{2\pi\sigma_w} e^{-\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}}} = \frac{\pi\cdot\sigma_w}{\sigma_v} e^{\frac{(w_0-m_w)^2}{2\cdot\sigma_w^2}} \left[1-\Phi\left(\frac{w_0-m_w}{\sigma_w}\right)\right] \qquad (2.17)$$

Substituting (2.13) into (2.11) gives the formula for the average number of emissions per unit of time

$$\bar{v}_{w_0} = \frac{\sigma_v}{2\pi\sigma_w} e^{-\frac{(w_0-m_w)^2}{2\sigma_w^2}}. \qquad (2.18)$$

The obtained results make it possible to take into account the stochastic nature of electricity consumption for a given period of time.

For a more convenient application of the formulas obtained above, it seems appropriate to present them in a dimensionless form, using the theory of similarity and dimensional analysis [9]. This approach makes it possible to transform variables into multiplicative complexes, reducing the number of independent variables, which simplifies research. In the dimensionless form, formulas (1.15),..., (1.18) take the following form

$$\hat{\bar{t}}_{\hat{w}_0} = 1 - \Phi\left(\hat{w}_0 - \hat{m}_w\right), \qquad (2.15')$$

$$\hat{\bar{n}}_{\hat{w}_0} = \hat{\sigma}_v e^{-\frac{(\hat{w}_0-\hat{m}_w)^2}{2}}, \qquad (2.16')$$

$$\bar{\tau}_{\hat{w}_0} = \frac{\pi}{\hat{\sigma}_v} e^{\frac{(\hat{w}_0-\hat{m}_w)^2}{2}} [1 - \Phi(\hat{w}_0 - \hat{m}_w)], \qquad (2.17')$$

$$\bar{v}_{\hat{w}_0} = \frac{1}{2\pi\hat{\sigma}_w} e^{-\frac{(\hat{w}_0-\hat{m}_w)^2}{2}}, \qquad (2.18')$$

where $\hat{\hat{t}}_{\widehat{w}_0} = \frac{2 \cdot \bar{t}_{w_0}}{T}$, $\widehat{m}_w = \frac{m_w}{\sigma_w}$, $\widehat{w}_0 = \frac{w_0}{\sigma_w}$, $\hat{\hat{n}}_{\widehat{w}_0} = \frac{\bar{n}_{w_0} \cdot 2\pi}{T}$, $\hat{\sigma}_v = \frac{\sigma_v}{\sigma_w}$. (2.19)

Analysis of the given formulas shows that the variables are presented in multiplicative form, that is, in the form of division and product. In addition, the number of variables decreased from five to three, which greatly simplifies the research. The reverse transition from the dimensionless form to the dimensional form is carried out using formulas (2.19)

$$\bar{t}_{w_0} = \frac{T}{2} \hat{\hat{t}}_{\widehat{w}_0},\ m_w = \sigma_w \cdot \widehat{m}_w, w_0 = \sigma_w \cdot \widehat{w}_0, \bar{n}_{w_0} = \frac{T}{2\pi} \hat{\hat{n}}_{\widehat{w}_0}, \sigma_v = \sigma_w \cdot \hat{\sigma}_v, \bar{\tau}_{w_0} = \bar{\tau}_{\widehat{w}_0}, \bar{v}_{w_0} = \bar{v}_{\widehat{w}_0}. \quad (2.20)$$

As an example of modeling electricity consumption as a stochastic process, let's consider electricity consumption at the Kryvyi Rih iron ore basin mine. In fig. 2.1 presents a graph of power consumption during 50 hours. Analysis of the graph shown in Fig. 2.1, shows that power consumption is a stochastic process.

The average power consumption for a certain time (50 hours) was the value

$$\bar{w} = \frac{1}{50} \sum_{i=1}^{50} w_i = 2017 \text{ kW}. \quad (2.21)$$

In turn, the variance is equal to

$$D[W] = \frac{1}{49} \sum_{i=1}^{50} (w_i - \bar{w})^2 = 110596.5 \text{ kW}^2 \quad (2.22)$$

The correlation function of power consumption is determined by the formula:

$$K_w(l) = \frac{1}{50 - l + 1} \sum_{j=0}^{50-l} (w_j - \bar{w})(w_{j+l} - \bar{w})(\text{кВт})^2, (l = 0,1,\ldots,4)\ . \quad (2.23)$$

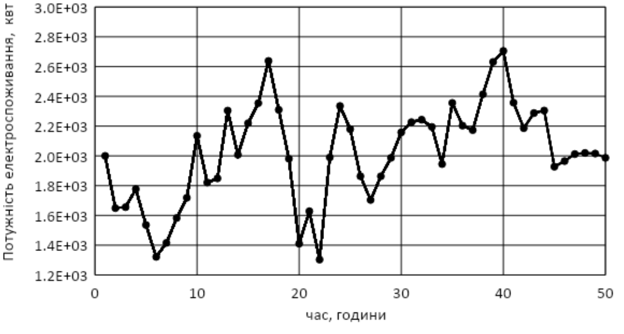

Figure 2.1. Power consumption schedule at the KZRK mine

In fig. 2.2 presents graphs of the normalized correlation function calculated by the formula

$$\widetilde{K}_w(l) = \frac{K_w(l)}{D[W]} \tag{2.24}$$

and the approximation of this function by the formula

$$\widetilde{K}_w^a(\tau) = e^{-\alpha\cdot|\tau|}(1 + \alpha \cdot |\tau|). \tag{2.25}$$

The application of the least squares method to the ordinates of the statistical normalized correlation function (2.23) made it possible to find the value of the parameter in the formula (2.25), which is equal to

$$\alpha = 1.4. \tag{2.26}$$

As a result, formula (2.25) takes the form

$$\widetilde{K}_w^a(\tau) = e^{-1.4\cdot|\tau|}(1 + 1.4 \cdot |\tau|)\ . \tag{2.27}$$

Analysis of the location of the graphs in fig. 2.2 shows a fairly satisfactory approximation of them.

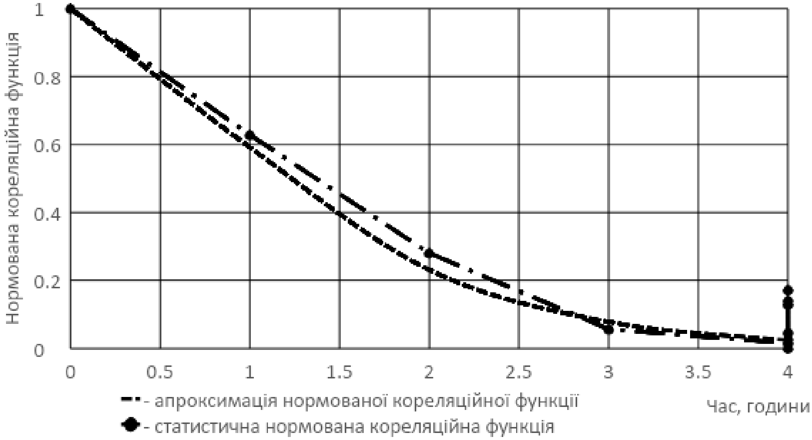

Figure 2.2 Graphs of the statistical normalized correlation function (2.22) and its approximation by the formula (2.25)

To confirm this conclusion, the determination index was calculated according to the formula

$$R^2 = 1 - \frac{S_a^2}{D[\widetilde{K}_w]}, \tag{2.28}$$

where $S_a^2 = \frac{1}{4}\sum_{l=0}^{4} \quad (\widetilde{K}_w(l) - e^{-1.4\cdot l}(1 + 1.4 \cdot l))^2$.

Calculation according to the formula (2.27) taking into account the numerical results gave the value

$$R^2 = 1 - \frac{0.00108}{0.1731} = 0.994. \qquad (2.29)$$

The value of the determination index (2.29) allows us to state that, according to the Chaddock scale, there is a very high strength of connection between the variables [10].

The study of the statistical material of power consumption at the KZRK mine showed that there is a normal stationary stochastic process with parameters determined by formulas (2.19) and (2.20). As a result, the formula for the power consumption density distribution will be written in the form

$$f_1(w) = \frac{1}{332.56\sqrt{2\pi}} e^{-\frac{(w-2017)^2}{2\cdot 110596.5}} . \qquad (2.30)$$

This allows you to apply the calculation formulas given above.

Taking into account (2.20) and (2.25), the formula for calculating the correlation function of power consumption has the form

$$K_w(\tau) = 110596.5 \cdot e^{-1.4\cdot|\tau|}(1 + 1.4 \cdot |\tau|). \qquad (2.31)$$

Then the variance of the rate of change of power consumption is calculated as follows

$$\sigma_v^2 = -\frac{d^2}{d\tau^2} K_w(0) = \sigma_w^2 \cdot \alpha^2. \qquad (2.32)$$

Taking into account the numerical values (2.20) and (2.24), we will have

$$\sigma_v^2 = 110596.5 \cdot 1.4^2 = 216769.1 \qquad (2.33)$$

To find the average time of power consumption values above the given level, we use the formula (2.15') taking into account (2.21) and (2.22)

$$\hat{\bar{t}}_{\widehat{w}_0} = 1 - \Phi(\widehat{w}_0 - 6.1) . \qquad (2.34)$$

In fig. 1.3 presents a graph of the dependence of the dimensionless average time of the power consumption value above the specified dimensionless level (2.34). Analysis of the graph shows that in a dimensionless form, as the level of power consumption increases, the average time the power consumption stays above this level decreases.

To move to dimensional values, we will use formulas (2.20). Let

$$\widehat{w}_0 = 6.6, \qquad (2.35)$$

then, according to the function (2.34) and the graph in Fig. 2.3 takes place

$$\hat{\bar{t}}_{\widehat{w}_0} = 0.62. \qquad (2.36)$$

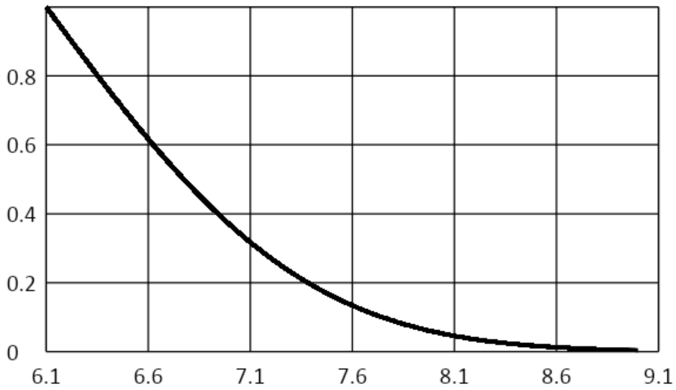

Figure 2.3. Dependence graph in a dimensionless form of the average time of stay of power consumption values above the given level of power consumption

If we assume that the observation time is equal to a day, i.e. $T = 24$ hour, and $\sigma_w = 332.56$ kW, then the average power consumption time during the day is higher

$$w_0 = 2195 \text{ kW}$$

will constitute

$$\bar{t}_{2195} = 12 \cdot 0.62 = 7.44 \text{ h}.$$

To find the average amount of emissions above a given level of power consumption, we use the formula (2.16'), which, according to (2.21), takes the form

$$\hat{\bar{n}}_{\hat{w}_0} = \hat{\sigma}_v e^{-\frac{(\hat{w}_0 - 6.1)^2}{2}}. \tag{2.37}$$

In fig. 2.4 presents graphs of the function (2.37). The root mean square deviation of the rate of change of power consumption is selected as a parameter. Analysis of the graphs shown in fig. 2.4, shows that with an increase in the given level of power consumption, the average number of emissions decreases, but with an increase in the average square deviation of the rate of change in power consumption, the average number of emissions increases.

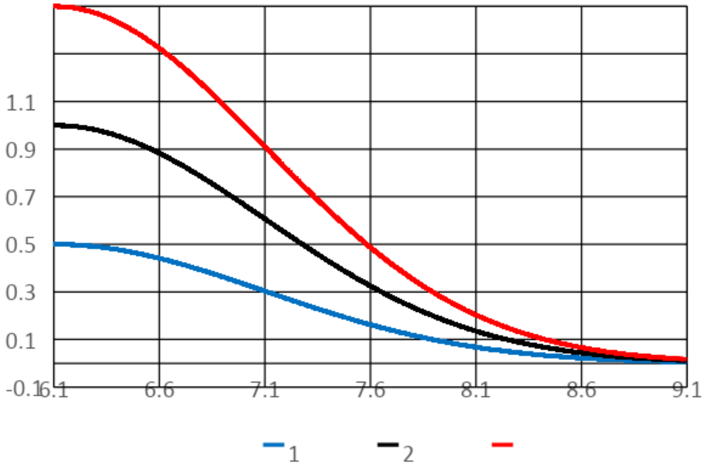

Figure 2.4. Graphs of dependence in dimensionless form of the average amount of emissions above the given level of power consumption on the given level of power consumption
(1- $\hat{\sigma}_v = 0.5$ *; 2-* $\hat{\sigma}_v = 1$*; 3-* $\hat{\sigma}_v = 1.5$*)*

If we assume that the observation time is equal to a day, i.e. $T = 24$ h, and $\sigma_w = 332.56$ kW and $\sigma_v = 465.6$ kW/h, then the average number of emissions during the day is above the given level of power consumption

$$w_0 = 2195 \quad \text{kW}$$

will be

$$\bar{n}_{2195} = \frac{24}{2\pi} 0.8825 = 3.37 \approx 3$$

In turn, to find the average duration of the release, we will use the formula (2.17'), which, taking into account (2.21), will take the form

$$\bar{\tau}_{\hat{w}_0} = \frac{\pi}{\hat{\sigma}_v} e^{\frac{(\hat{w}_0 - 6.1)^2}{2}} [1 - \Phi(\hat{w}_0 - 6.1)]. \qquad (2.38)$$

In fig. 2.5 presents in a dimensionless form graphs of the dependence of the average duration of emission above the given level of power consumption on the given level of power consumption according to formula (2.38). The analysis of the given graphs shows that with the increase in the value of the given level of power consumption, the average duration of emission above the given level of power consumption decreases. In addition, when the mean square deviation of the rate of change of power consumption increases, as a parameter, the average duration of emissions above a given level of power consumption decreases.

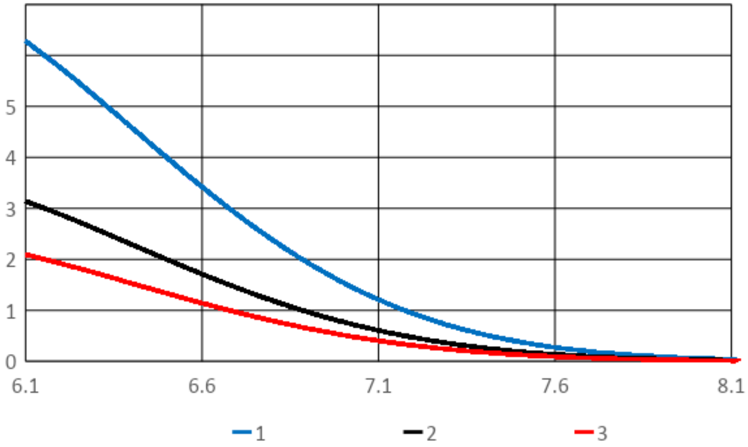

Figure 2.5. Graphs of dependence in a dimensionless form of the average duration of emissions above a given level of power consumption on the given level of power consumption
(1- $\hat{\sigma}_v = 0.5$ *; 2-* $\hat{\sigma}_v = 1$*; 3-* $\hat{\sigma}_v = 1.5$ *)*

If we assume that the observation time is equal to a day, i.e. $T = 24$ h, and $\sigma_w = 332.56$ kW and $\sigma_v = 465.6$ kW/h, then the average number of emissions during the day is higher than the power consumption level

$$w_0 = 2195 \text{ kW}$$

will be

$$\bar{\tau}_{2195} = 1.71 \text{ h}.$$

In total, let's consider the electricity consumption for a certain time, according to formulas (2.3) and (2.6). Considering (2.21), we have

$$m_q(T) = m_w \cdot T = 2017 \cdot T \text{ кВт-год}. \tag{2.38}$$

In turn

$$D[Q(T)] = 2\sigma_w^2 \int_0^T (T-\tau)\cdot e^{-\alpha\cdot\tau}(1+\alpha\cdot\tau)d\tau =$$

$\frac{2\sigma_w^2}{\alpha^2}[3(e^{-\alpha\cdot T}-1)+\alpha T(2+e^{-\alpha\cdot T})]$According to (2.22) and (2.31), we have

$$D[Q(T)] = 1.1285\cdot 10^5\cdot[3(e^{-1.4\cdot T}-1)+1.4\cdot T\cdot(2+e^{-1.4\cdot T})],$$

or

$$\sigma[Q(T)] = 335.93 \cdot \sqrt{3(e^{-1.4 \cdot T} - 1) + 1.4 \cdot T \cdot (2 + e^{-1.4 \cdot T})}. \quad (2.39)$$

Fig. 2.6 shows graphs of electricity consumption according to formula (2.38) taking into account the root mean square deviation (2.39) during the day.

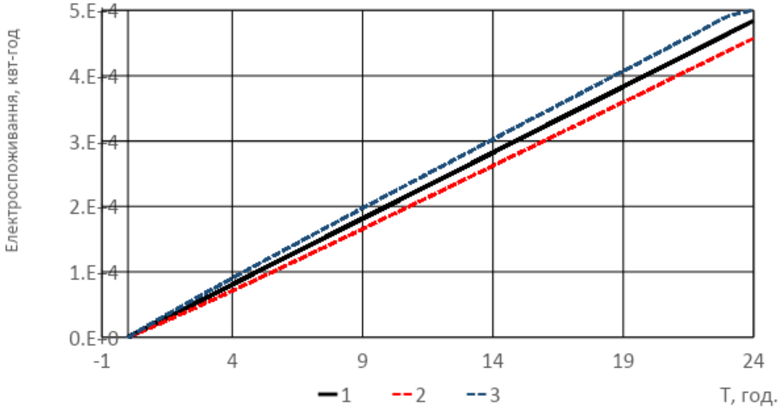

Figure 2.6. Graphs of electricity consumption during the day (1-average power consumption, 2- power consumption, reduced by the mean square deviation (2.39), 3- power consumption, increased by the mean square deviation (2.39))

Analysis of the graphs shown in Fig. 2.6 shows that the average power consumption increases with time. Along with this, the deviation of electricity consumption from the average electricity consumption increases linearly due to the mean square deviation (2.39), reaching a maximum for the final time of the day.

If the determined time is equal to a day, that is, $T = 24$ h, then according to (2.38) and (2.39), we have $m_q(24) = m_w \cdot 24 = 2017 \cdot 24 = 4.8408 \cdot 10^4$ kWh,

$$\sigma[Q(24)] = 2692 \text{ kW}.$$

Thus, the obtained formulas allow for a complete study of power consumption as a normal stochastic process within the framework of the correlation theory.

The study of electricity consumption as a stochastic process made it possible to build a mathematical model by using statistical material on the KZRK mine.

According to the synthesized model, the following stochastic characteristics of power consumption were determined as averages and variances, the average time of power consumption as a stationary random function above the given level w=wo during time, the average number of emissions of power consumption during this period of time, and the average duration of the emission.

2.2 Statistical analysis of time series of the electricity consumption - supply system

Determining stochasticity as one of the properties of the supply-consumption-production system, we consider it expedient to conduct research in the direction of building stochastic models for time series in the time domain and applying these models. If time varies discretely, then the time series is discrete. Observations of a discrete time series made at time points $t_1, t_2, \ldots, t_i, \ldots, t_N$, can be denoted by $z(t_1), z(t_2), \ldots, z(t_i), \ldots, z(t_N)$. If the observations are made at a fixed time interval Δt and there are N consecutive values of the observations of the series, we can write $z_1, z_2, \ldots z_i, \ldots z_N$, denoting the observations made at equidistant moments of time $t_0 + \Delta t, t_0 + 2\Delta t, \ldots, t_0 + i \cdot \Delta t, \ldots, t_0 + N\Delta t$. In the following, the values of t_0 and Δt are not important, but if it is necessary to accurately determine the observations, then it is necessary to specify their values. If we take t_0 as the beginning of time counting, i.e. $t_0 = 0$, and Δt as a unit of time, i.e. Δt=1, then z_i can be considered as an observation at the i-th moment of time.

One of the important applied tasks is to predict the future values of a time series based on its current and past values. In practice, there is always a need to forecast ahead for an interval called the warning time. The main feature in the development of stochastic time series models is the assumption of stationarity. A stationary stochastic time series is conveniently described by its mean, variance, and autocorrelation function. To estimate the average value of a discrete stochastic process, you can use the sample average

$$\bar{z} = \frac{1}{N}\sum_{i=1}^{N} z_i, \tag{2.40}$$

where $z_1, z_2, \ldots, z_N$ –time series values.

In turn, the variance of a discrete stochastic process is estimated using the sample variance

$$\sigma_z^2 = \frac{1}{N-1}\sum_{i=1}^{N} (z_i - \bar{z})^2. \quad (2.41)$$

To estimate the relationship between the values of the time series, autocorrelation is used with a delay k, which is equal to

$$\rho_k = \frac{1}{(N-1)\cdot\sigma_z^2}\sum_{i=1}^{N-k} (z_i - \bar{z})(z_{i+k} - \bar{z}). \quad (2.42)$$

Discrete time series in which successive values are dependent should naturally be considered as generated by a sequence of independent pulses a_i. These impulses are realizations of random variables with a normal distribution with zero mean and variance σ_a^2. The sequence of random values $a_i, a_{i-1}, \ldots$ is called "white noise". The white noise a_i can be transformed into the process under study z_i using a linear filter. The filtering operation consists in computing the weighted sum of the previous observations, so that

$$z_i = \bar{z} + a_i + \psi_1 \cdot a_{i-1} + \psi_2 \cdot a_{i-2} + \ldots \quad (2.43)$$

where $\psi_1, \psi_2, \ldots$ a sequence of filter "weights".

White noise can be thought of as a pulse train consisting of a sequence of uncorrelated random variables with zero mean and constant variance

$$\bar{a} = \frac{1}{N}\sum_{i=1}^{N} a_i = 0\ ,\ D[a] = \sigma_a^2. \quad (2.44)$$

Since the random variables are uncorrelated, the autocorrelation function of white noise will be written as

$$\rho_k = \{1, \ \ k = 0, 0, \ \ k \neq 0. \quad (2.45)$$

If two variables are considered, one of which is the input x_i and the second is the output y_i, then they can be connected by a linear filter

$$y_i = k \cdot x_i + k_1 \cdot x_{i-1} + k_2 \cdot x_{i-2} + \ldots, \quad (2.46)$$

where $k, k_1, k_2, \ldots$ – sequence of weights.

According to the current research, the structure of the function (2.46) is determined by its static part, that is, it has the form

$$y_i = k \cdot x_i, i = 1,2,\ldots,N \quad (2.47)$$

Given that the number of equations in (2.47) is greater than the number of unknowns ($N > 1$), we have a system of equations N with one unknown k. It is clear that such a system of equations is incompatible. This system (2.47) can be solved using the method of least squares (MLS), that is, by minimizing the function of the total discrepancy in the form of the sum of the squares of the discrepancies of each of the equations (2.47)

$$F(k)=\sum_{i=1}^{N}\quad(y_i-k\cdot x_i)^2\rightarrow\min_{k}. \qquad (2.48)$$

The simple form of the function (2.47) allows solving the minimization problem (2.48) by equating the zero derivative of the function (2.48), i.e.

$$\frac{dF(k)}{dk}=0. \qquad (2.49)$$

Since the function (2.47) is linear with respect to the parameter, then $F(k)$is a quadratic function, which determines the linearity of equation (2.49). Indeed, calculating the derivative in (2.49), we consistently have

$$\frac{dF(k)}{dk}=-2\sum_{i=1}^{N}\quad(y_i-k\cdot x_i)\cdot x_i=0,$$

$$\sum_{i=1}^{N}\quad(y_i\cdot x_i-k\cdot x_i^2)=0\ k\cdot\sum_{i=1}^{N}\quad x_i^2=\sum_{i=1}^{N}\quad y_i\cdot x_i. \qquad (2.50)$$

From the last equation, we find the optimal value of the parameter

$$k_0=\frac{\sum_{i=1}^{N}\quad y_i\cdot x_i}{\sum_{i=1}^{N}\quad x_i^2}. \qquad (2.51)$$

Thus, according to (2.47) and (2.51), the mathematical model will be presented in the form

$$\hat{y}=k_0\cdot x. \qquad (2.52)$$

The obtained model (1.52) allows you to determine the quantitative dependence of the output variable on the input variable.

To analyze the quality of the relationship between variables in model (2.47) taking into account (2.51), it is advisable to use the Chaddock scale, which allows you to establish the qualitative nature of the relationship between variables based on the value of the correlation coefficient.

Table 2.1 shows the Chaddock scale below.

Table 2.1

Chaddock scale

Coefficient correlations	0,1-0,3	0,3-0,5	0,5-0,7	0,7-0,9	0,9-0,99
Connection	weak	moderate	noticeable	high	very high

The correlation coefficient is calculated using the formula

$$r=\sqrt{1-\frac{\sum_{i=1}^{N}\quad(y_i-k_0\cdot x_i)^2}{\sum_{i=1}^{N}\quad y_i^2}}. \qquad (2.53)$$

Then, according to the Chaddock scale, a conclusion is made about the strength of the relationship between the variables.

The application of statistical methods to the analysis of real data is considered below. The given data are time series with an interval of $\Delta t=6$

hours. In addition, it should be emphasized that the values of the time series were formed by accumulating these variables during a given interval.

In the table 2.2 presents calculation data for the Artem mine on the UPP (1 transformer).

The mathematical model in this case, according to (2.47), has the form

$$v_i = k \cdot p_i, \;\; (i = 1,2,\ldots,28). \qquad (2.54)$$

The value of parameter k can be found using the formula (2.51)

$$k_0 = \frac{\sum_{i=1}^{N} \;\; v_i \cdot p_i}{\sum_{i=1}^{N} \;\; p_i^2} \; . \qquad (2.55)$$

According to the data given in the last line of the table. 2.1, using formula (2.55) we find

$$k_0 = \frac{17255321}{8952023} = 1.928. \qquad (2.56)$$

The correlation coefficient is found by formula (2.53), according to the data in the last line of the table. 2.2

$$r = \sqrt{1 - \frac{\sum_{i=1}^{28} \;\; (v_i - 1.928 \cdot p_i)^2}{\sum_{i=1}^{28} \;\; v_i^2}} = \sqrt{1 - \frac{3687660}{36947861}} = 0.949. \qquad (2.57)$$

According to the Chaddock scale, the value of the correlation coefficient (2.57) indicates a very high relationship between variables, that is, a mathematical model

$$v_{\text{м}} = 1{,}928 \cdot p. \qquad (2.58)$$

is adequate.

Table 2.2

Analytical and calculation table of the mathematical model for the Artem mine on the UPP (1 transformer).

№	p_i, **kWh**	v_i, **tons**	p_i^2	$v_i \cdot p_i$	**Model** $v_{м,i} = k_0 \cdot p_i$	v_i^2	$(v_i - v_{\text{м},i}$
1	440	850	193600	374000	848.3	722500	2.8224
2	585.6	800	342927.4	468480	1129.0	640000	108265.2
3	648.7	1524	420811.7	988618.8	1250.7	2322576	74696.39
4	620.1	1098	384524	680869.8	1195.6	1205604	9516.549
5	755.9	1211	571384.8	915394.9	1457.4	1466521	60700.74
6	661.2	1470	437185.4	971964	1274.8	2160900	38105.54
7	557.2	595	310471.8	331534	1074.3	354025	229710.9
8	294.5	774	86730.25	227943	567.8	599076	42520.09
9	508	860	258064	436880	979.4	739600	14262.09
10	500.5	1596	250500.3	798798	965.0	2547216	398206.4
11	483.6	921	233869	445395.6	932.4	848241	129.5226
12	711.3	1452	505947.7	1032808	1371.4	2108304	6498.553

13	562.8	838	316743.8	471626.4	1085.1	702244	61047.74
14	773.1	1354	597683.6	1046777	1490.5	1833316	18642.3
15	546.1	1764	298225.2	963320.4	1052.9	3111696	505690.5
16	417.1	668	173972.4	278622.8	804.2	446224	18541.94
17	517.9	1403	268220.4	726613.7	998.5	1968409	163611.2
18	531.8	1039	282811.2	552540.2	1025.3	1079521	187.4051
19	457.9	847	209672.4	387841.3	882.8	717409	1283.875
20	571	1280	326041	730880	1100.9	1638400	32081.11
21	583.7	1664	340705.7	971276.8	1125.4	2768896	290118.4
22	428	1363	183184	583364	825.2	1857769	289246
23	732.7	336	536849.3	246187.2	1412.6	112896	1159166
24	528.2	1139	278995.2	601619.8	1018.4	1297321	14551.69
25	610.2	974	372344	594334.8	1176.5	948676	40992.32
26	451.5	1011	203852.3	456466.5	870.5	1022121	19742.5
27	585.4	844	342693.2	494077.6	1128.7	712336	81026.31
28	473.3	1008	224012.9	477086.4	912.5	1016064	9115.972
Average	554.9	1095.8					
Dispersion	12234.1	123139.7					
Amount			8952023	17255321		36947861	3687660

Figures 2.7 and 2.8 show graphs of the data in the table. 1.2

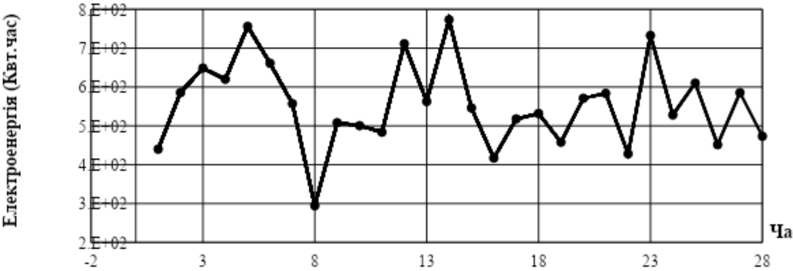

Figure 2.7. The graph of the dependence of the amount of electricity on time

In fig. 2.8 graphs of the dependence of product production and its model on time are presented in black and red colors. The analysis of the presented graphs confirms the results about the adequacy of the mathematical model, which were obtained analytically.

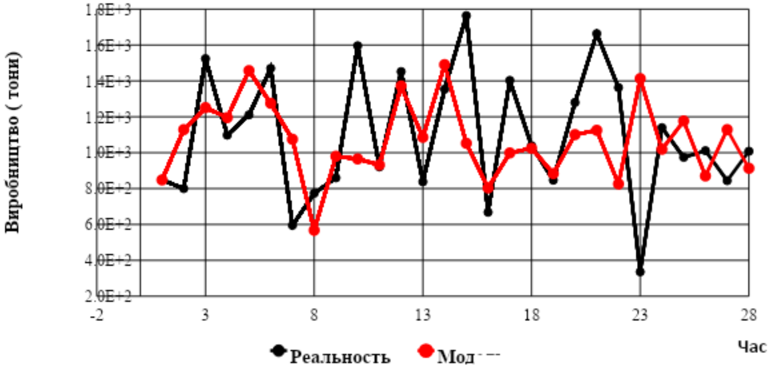

Figure 2.8 Graph of dependence of product production and its model on time

Next, we will conduct a study on the stochasticity of the time series, which are formed by the electricity consumed for the corresponding volume of production.

Analysis of the graph of the dependence of electricity on time, which is presented in Fig. 2.7, indicates its stochasticity. In the table 2.2, its average and variance are presented in the last terms

$$\bar{p} = 554.9 \text{ КВт.-час}, \quad D[P] = 12234.1 \text{ kWh}^2. \qquad (2.58)$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.2)

$$\rho_k = \frac{1}{(28-1)\cdot 12234.1}\sum_{i=1}^{28-k} (p_i - 554.9)(p_{i+k} - 554.9),(k = 0,1,2,\ldots,5). \qquad (2.59)$$

The first 5 values of sample autocorrelation are given in table 1.3 and shown in fig. 2.9.

Table 2.3

Sample autocorrelation values

k	0	1	2	3	4	5
ρ_k	1	-0,021	0,092	-0,230	-0,364	-0,378

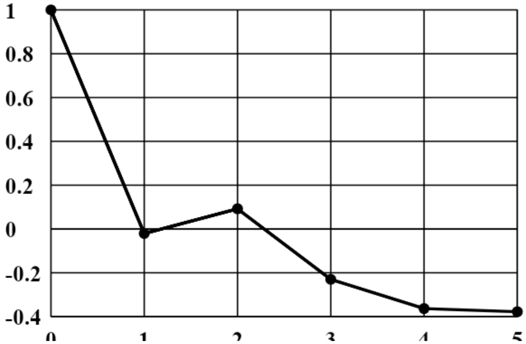

Figure 2.9 Autocorrelation function of electricity supply data Artem mines (1 transformer)

The analysis of the autocorrelation function shows that the electric power values are practically independent of each other, that is, they are white noise. As a result, the mathematical model of the stochastic time series takes the form

$$p_i = 554.9 + a_i\ ,\ (i = 1,2,\ldots,28), \qquad (2.59)$$

where $\bar{a} = 0,\ \sigma_a^2 = 12234.1$.

Similarly, an analysis of the stochasticity of the time series of product production is carried out in Table B. 2.2, its average and variance are presented in the last terms

$$\bar{v} = 1095.8 \text{ tons}, \quad D[V] = 123139.7 \text{ tons}^2. \qquad (2.60)$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.42)

$$\rho_k = \frac{1}{(28-1)\cdot 123139.7}\sum_{i=1}^{28-k} (v_i - 1095.8)(v_{i+k} - 1095.8),(k = 0,1,2,\ldots,5). \qquad (2.61)$$

The first 5 values of the sample autocorrelation are given in the table. 2.4 and shown in fig. 2.10.

Table 2.4

Sample autocorrelation values

k	0	1	2	3	4	5
ρ_k	1	-0,187	-0,132	0,016	-0,052	0,047

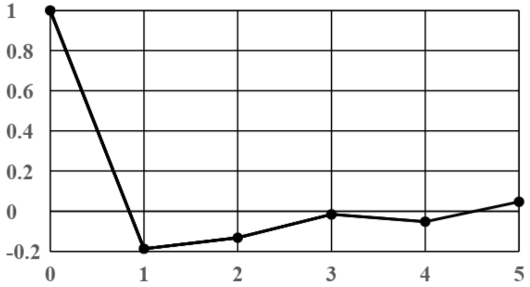

Figure 2.10 Autocorrelation function of production data Artem mines (1 transformer)

Analysis of the autocorrelation function shows that the values of product production are practically independent of each other, that is, they are white noise. As a result, the mathematical model of the stochastic time series takes the form

$$v_i = 1095.8 + a_i,\ (i = 1,2,\ldots,28), \qquad (2.62)$$

where $\bar{a} = 0$, $\sigma_a^2 = 123139.7$.

Similarly, data analysis is carried out, respectively, Artem mine on UPS (2 transformer). In the table 2.5 presents relevant data.

According to the data given in the last line of Table 2.5, by formula (2.16) we find

$$k_0 = \frac{167860}{62692} = 2.678\,. \qquad (2.63)$$

Table 2.5

Analytical and calculation table of the mathematical model for the Artem mine on the UPP (2 transformer).

№	p_i, **kWh**	v_i, **tons**	p_i^2	$v_i \cdot p_i$	**Model** $v_{м,i} = k_0 \cdot p_i$	v_i^2	$(v_i - v_{м,i})^2$
1	70.7	128	4998.49	9049.6	189.3	16384	3761.9
2	44.8	64	2007.04	2867.2	120.0	4096	3133.1
3	73.9	168	5461.21	12415.2	197.9	28224	894.3
4	51.4	168	2641.96	8635.2	137.6	28224	921.2
5	73.8	152	5446.44	11217.6	197.6	23104	2082.7
6	63	208	3969	13104	168.7	43264	1543.4
7	52	40	2704	2080	139.3	1600	9851.8
8	46.1	32	2125.21	1475.2	123.5	1024	8364.2

9	4.6	0	21.16	0	12.3	0	151.8
10	30.6	112	936.36	3427.2	81.9	12544	903.2
11	21.6	88	466.56	1900.8	57.8	7744	909.3
12	78.4	240	6146.56	18816	210.0	57600	902.7
13	50.6	144	2560.36	7286.4	135.5	20736	72.1
14	64.2	268	4121.64	17205.6	171.9	71824	9229.9
15	58.3	160	3398.89	9328	156.1	25600	15.0
16	34.3	48	1176.49	1646.4	91.9	2304	1923.3
17	64.2	216	4121.64	13867.2	171.9	46656	1942.4
18	62.6	168	3918.76	10516.8	167.6	28224	0.1
19	35.1	96	1232.01	3369.6	94.0	9216	4.0
20	46.1	160	2125.21	7376	123.5	25600	1335.5
21	55.8	220	3113.64	12276	149.4	48400	4979.8
Average	51.53	137.1					
Dispersion	346.68	5369.8					
Amount			62693	167860		502368	52922

The correlation coefficient is found by formula (2.53), according to the data in the last line of the table. 2.5.

$$r = \sqrt{1-\frac{\sum_{i=1}^{21} \quad (v_i - 2.678 \cdot p_i)^2}{\sum_{i=1}^{21} \quad v_i^2}} = \sqrt{1-\frac{52922}{502368}} = 0.946. \qquad (2.64)$$

According to the Chaddock scale, the value of the correlation coefficient (2.64) indicates a very high relationship between variables, that is, a mathematical model

$$v_{м} = 2{,}678 \cdot p \qquad (2.65)$$

is adequate.

In fig. 2.11 and 2.12 present graphs of the data in the table. 2.5.

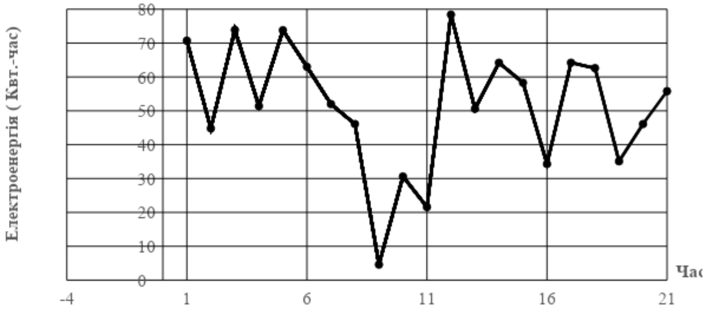

Figure 2.11. Graph of dependence of electricity amount on time Artem mine (2 transformer)

Figure 2.12. Graph of dependence of production and its model on time in relation to Artem mine (2 transformer)

In fig. 2.12 graphs of the dependence of production and its model on time are presented in black and red colors. The analysis of the presented graphs confirms the results about the adequacy of the mathematical model, which were obtained analytically.

Next, we examine the stochasticity of the time series formed by the consumed electricity and the volume of production.

Analysis of the graph of the dependence of electricity on time, which is presented in fig. 2.11, indicates its stochasticity. In the table 2.5 its average and variance are presented in the last terms

$$\bar{p} = 51.5 \text{ КВт.-час}, \quad D[P] = 346.7 \text{ kWh}^2. \qquad (2.66)$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.42)

$$\rho_k = \frac{1}{(21-1)\cdot 346.7} \sum_{i=1}^{21-k} (p_i - 51.5)(p_{i+k} - 51.5) . \qquad (2.67)$$

The first 5 values of the sample autocorrelation are given in the table. 2.6 and shown in fig. 2.13.

Table 2.6

Sample autocorrelation values

k	0	1	2	3	4	5
ρ_k	1	0,164	0,082	-0,202	-0,399	-0,159

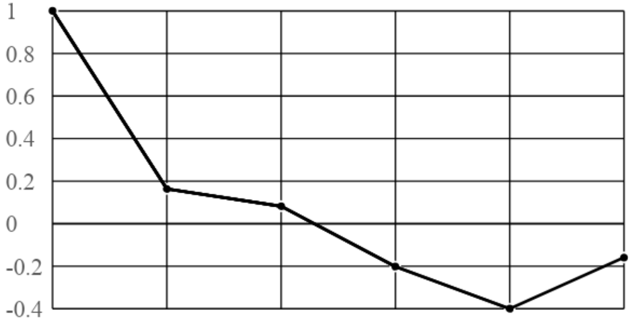

Figure 2.13. Autocorrelation function of electricity data

The analysis of the autocorrelation function shows that the electric power values are practically independent of each other, that is, they are white noise. As a result, the mathematical model of the stochastic time series takes the form

$$p_i = 51.5 + a_i \ , (i = 1,2,\dots,21), \tag{2.68}$$

where $\bar{a} = 0$, $\sigma_a^2 = 346.7$.

Similarly, an analysis of the stochasticity of the product production time series is carried out. In the table 2.5 its average and variance are presented in the last terms

$$\bar{v} = 137.8 \ \text{тони}, \ \ D[V] = 5369.8 \text{ tons}^2. \tag{2.69}$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.43)

$$\rho_k = \frac{1}{(21-1)\cdot 5369.8} \sum_{i=1}^{21-k} \ (v_i - 137.1)(v_{i+k} - 137.1) \tag{2.70}$$

The first 5 values of the sample autocorrelation are given in the table. 2.7 and shown in fig. 2.14.

Table 2.7

Sample autocorrelation values

k	0	1	2	3	4	5
ρ_k	1	0,167	0,084	-0,046	-0,281	-0,356

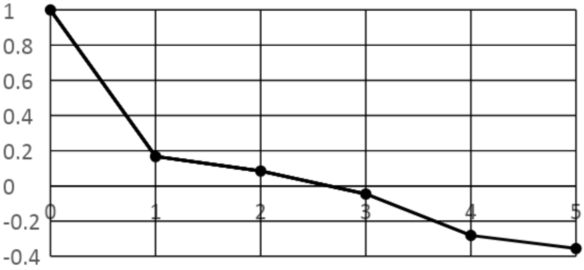

Figure 2.14. Autocorrelation function of data on the production of the Artem mine (2 transformers)

The analysis of the autocorrelation function shows that the values of the production value are practically independent of each other, that is, they are white noise. As a result, the mathematical model of the stochastic time series takes the form

$$v_i = 137.8 + a_i\ , (i = 1,2,\ldots,21), \qquad (2.71)$$

where $\bar{a} = 0$, $\sigma_a^2 = 5369.8$.

Next, the data analysis is carried out according to the Tsentralna mine UPP 3 (1 transformer). In the table 2.8 presents relevant data.

Table 2.8

Analytical and calculation table of the mathematical model regarding Tsentralna mine on UPP 3 (1 transformer).

№	p_i, **kWh**	v_i, **tons**	p_i^2	$v_i \cdot p_i$	**Model** $v_{м,i} = k_0 \cdot p_i$	v_i^2	$(v_i - v_{м,i})^2$
1	165.1	27258.0	297	49034.7	184.912	88209	12563.7
2	211.9	44901.6	0	0	237.328	0	56324.6
3	118.6	14066.0	0	0	132.832	0	17644.3
4	177.8	31612.8	140	24892	199.136	19600	3497.1
5	212.4	45113.8	210	44604	237.888	44100	777.7
6	284.6	80997.2	245	69727	318.752	60025	5439.4
7	121.3	14713.7	128	15526.4	135.856	16384	61.7
8	195.7	38298.5	122	23875.4	219.184	14884	9444.7
9	266.1	70809.2	455	121075.5	298.032	207025	24639.0
10	166.4	27689.0	332	55244.8	186.368	110224	21208.7
11	208.8	43597.4	332	69321.6	233.856	110224	9632.2
12	251.6	63302.6	260	65416	281.792	67600	474.9
13	148.5	22052.3	122	18117	166.32	14884	1964.3

14	221.3	48973.7	252	55767.6	247.856	63504	17.2
15	216.2	46742.4	385	83237	242.144	148225	20407.8
Average	197.7533	218.6667					
Dispersion	2395.168	17690.1					
Amount			620128.1	695839		964888	184097.3

According to the data given in the last line of the table. 2.8, using formula (2.55) we find

$$k_0 = \frac{695839}{620128.1} = 1.12 \qquad (2.72)$$

The correlation coefficient is found by formula (2.53), according to the data in the last line of the table. 2.8.

$$r = \sqrt{1 - \frac{\sum_{i=1}^{21} \quad (v_i - 1.12 \cdot p_i)^2}{\sum_{i=1}^{21} \quad v_i^2}} = \sqrt{1 - \frac{184097.3}{964888}} = 0.90 \qquad (2.73)$$

According to the Chaddock scale, the value of the correlation coefficient (2.73) indicates a very high relationship between variables, that is, a mathematical model

$$v_{\text{м}} = 1{,}12 \cdot p \qquad (2.74)$$

is adequate.

In fig. Figures 2.14 and 2.15 present graphs of the data in the table. 2.8.

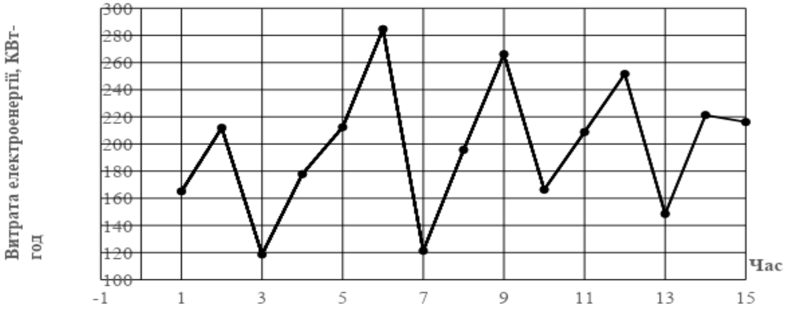

Figure 2.14. The graph of the dependence of the amount of electricity on time Tsentralna mine (1 transformer)

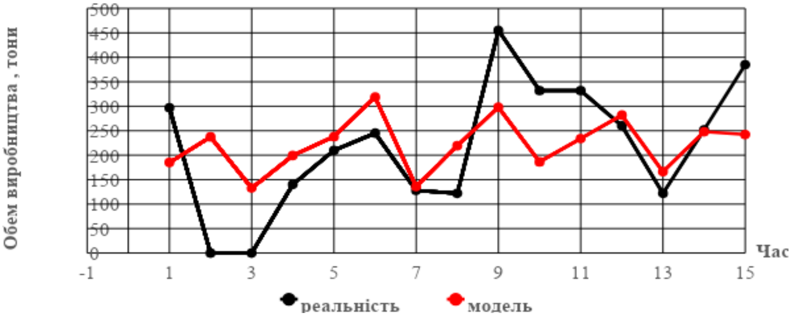

Figure 2.15. The graph of the dependence of production and its model on time Tsentralna mine (1 transformer)

In fig. 2.15 graphs of dependence of production and its model on time are presented in black and red colors. The analysis of the presented graphs confirms the results about the adequacy of the mathematical model, which were obtained analytically.

Next, we examine the stochasticity of the time series formed by the values of the quantities that determine the power supply and the volume of production.

Analysis of the graph of the dependence of electricity on time, which is presented in Fig. 2.9, indicates its stochasticity. In the table 2.8 its average and variance are presented in the last terms

$$\bar{p} = 197.8 \text{ КВт.-год}, \; D[P] = 2395.2 \text{ kWh}^2. \qquad (2.75)$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.43)

$$\rho_k = \frac{1}{(15-1)\cdot 2395.2} \sum_{i=1}^{15-k} (p_i - 197.8)(p_{i+k} - 197.8). \qquad (2.76)$$

The first 4 values of sample autocorrelation are given in the table. 2.9 and shown in fig. 2.16.

Table 2.9

Value of sample autocorrelation

k	0	1	2	3	4
ρ_k	1	-0.48	-0.40	0.345	0.035

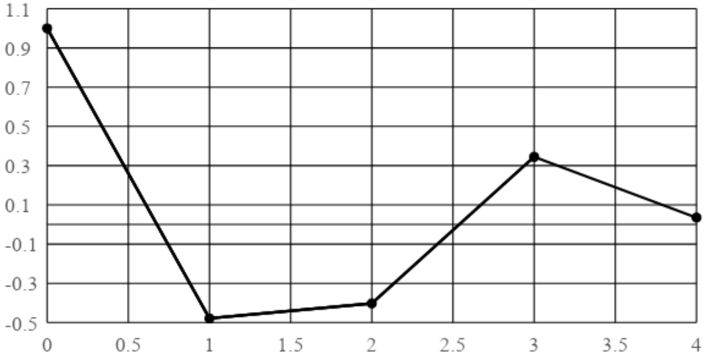

Figure 2.16. Autocorrelation function of Tsentralna mine electricity supply data (1 transformer)

The analysis of the autocorrelation function is characterized by a sign-changing correlation with a tendency to decay as the delay increases. Thus, it can be assumed that there is a first-order autoregressive process, which has the form

$$p_i = 197.8 - 0.48 \cdot (p_{i-1} - 197.8) + a_i. \qquad (2.77)$$

Similarly, an analysis of the stochasticity of the production time series is carried out. In the table 2.8 its average and variance are presented in the last terms

$$\bar{v} = 218.7 \text{ тони}, \quad D[V] = 17690.1 \text{ tons}^2. \qquad (2.78)$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.43)

$$\rho_k = \frac{1}{(15-1)\cdot 17690.1} \sum_{i=1}^{15-k} \quad (v_i - 218.7)(v_{i+k} - 218.7). \qquad (2.79)$$

The first 4 values of sample autocorrelation are given in the table. 2.10 and shown in fig. 2.17.

Table 2.10

Value of sample autocorrelation

k	0	1	2	3	4
ρ_k	1	0.12	-0.32	-0.037	0.12

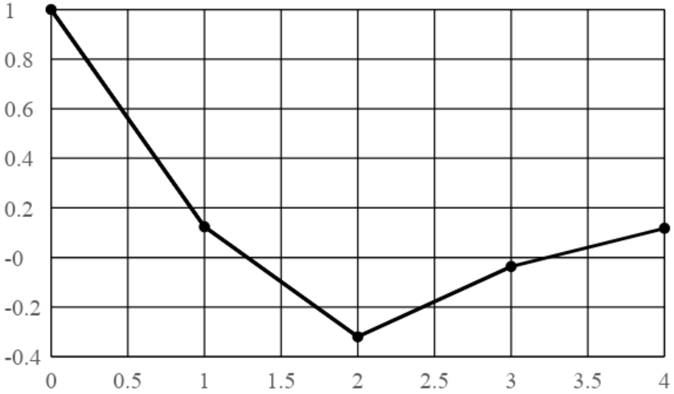

Figure 2.17 Autocorrelation function of manufacturer data Tsentralna mine (1 transformer)

The analysis of the autocorrelation function shows that the values of the production values are practically independent of each other, that is, they are white noise. As a result, the mathematical model of the stochastic time series takes the form

$$v_i = 218.7 + a_i \quad (i = 1,2,\dots,15), \qquad (2.79)$$

where $\bar{a} = 0,\ \sigma_a^2 = 17690.1$

Next, the analysis of data on Tsentralna mine UPP 3 (2 transformer) is carried out.

Table 2.11 presents the relevant data.

Table 2.11

Analytical and calculation table of the mathematical model regarding Tsentralna mine on UPP (2 transformer).

№	p_i, **kWh**	v_i, **tons**	p_i^2	$v_i \cdot p_i$	**Model** $v_{м,i} = k_0 \cdot p_i$	v_i^2	$(v_{м,i} - v_i)^2$
1	105.7	140	11172.49	14798	305.473	19600	27381.31
2	65.5	245	4290.25	16047.5	189.295	60025	3103.047
3	50.1	0	2510.01	0	144.789	0	20963.85
4	115.7	472	13386.49	54610.4	334.373	222784	18941.19
5	89.4	350	7992.36	31290	258.366	122500	8396.79
6	0	560	0	0	0	313600	313600
7	174.1	490	30310.81	85309	503.149	240100	172.8962

8	136.7	350	18686.89	47845	395.063	122500	2030.674
9	145.2	385	21083.04	55902	419.628	148225	1199.098
10	147.6	315	21785.76	46494	426.564	99225	12446.53
11	158.7	402	25185.69	63797.4	458.643	161604	3208.429
12	179.8	368	32328.04	66166.4	519.622	135424	22989.23
13	134.9	525	18198.01	70822.5	389.861	275625	18262.55
14	212.2	542	45028.84	115012.4	613.258	293764	5077.703
15	183.7	858	33745.69	157614.6	530.893	736164	106999
Average	126.62	400.1333					
Dispersion	3229.643	39252.84					
Amount			285704.4	825709.2		2951140	564772.3

According to the data given in the last line of the table. 2.11, using formula (2.55) we find

$$k_0 = \frac{825709.2}{285704.4} = 2.89\ . \tag{2.80}$$

The correlation coefficient is found by formula (2.53), according to the data in the last line of the table. 2.11.

$$r = \sqrt{1 - \frac{\sum_{i=1}^{15}\ (v_i - 2.89 \cdot p_i)^2}{\sum_{i=1}^{15}\ v_i^2}} = \sqrt{1 - \frac{564772.3}{2951140}} = 0.899. \tag{2.81}$$

According to the Chaddock scale, the value of the correlation coefficient (2.53) indicates a very high relationship between variables, that is, a mathematical model

$$v_{\text{м}} = 2.89 \cdot p \tag{2.82}$$

is adequate.

In fig. 2.18 and 2.19 present graphs of the data in the table. 2.11.

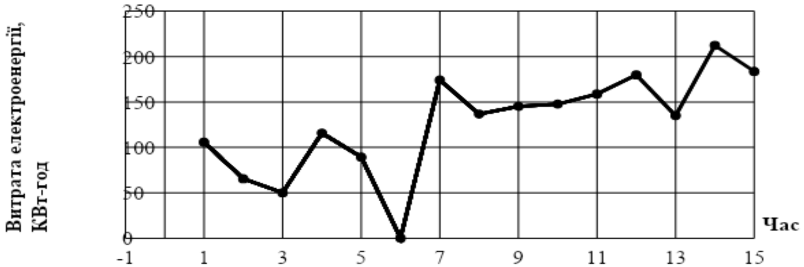

Figure 2.18. Graph of the dependence of the amount of electricity supply on the time of Tsentralna mine on the UPS (2 transformer).

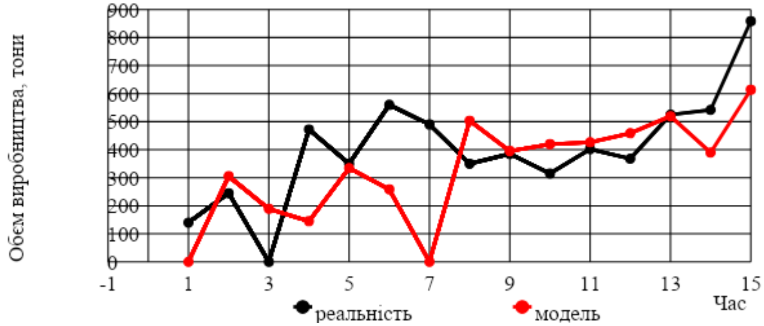

Figure 2.19. The graph of the dependence of production and its model on time Tsentralna mine on UPP (2 transformer).

And Fig. 2.19 graphs of the dependence of product production and its model on time are presented in black and red colors. The analysis of the presented graphs confirms the results about the adequacy of the mathematical model, which were obtained analytically.

Next, we examine the stochasticity of the time series formed by the conception of the electricity supply and the volume of production.

Analysis of the graph of the dependence of electricity on time, which is presented in fig. 2.18, indicates its stochasticity. In the table 2.11, its average and variance are presented in the last lines

$$\bar{p} = 126.6 \text{ КВт-год}, \qquad D[P] = 3229.6 \text{ kWh}^2 \tag{2.83}$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.43)

$$\rho_k = \frac{1}{(15-1)\cdot 3229.6} \sum_{i=1}^{15-k} (p_i - 126.6)(p_{i+k} - 126.6). \tag{2.84}$$

The first 4 values of sample autocorrelation are given in the table. 2.12 and shown in fig. 2.20.

Table 2.12

Value of sample autocorrelation

k	0	1	2	3	4
ρ_k	1	0.195	0.227	0.544	0.358

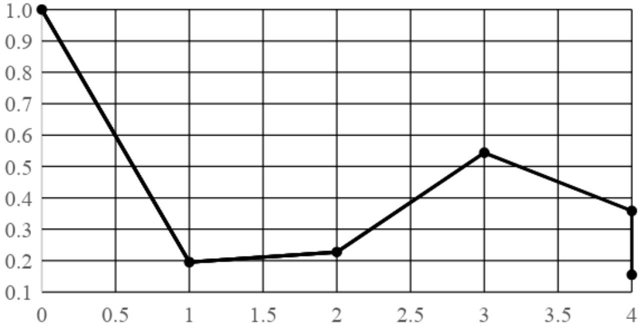

Figure 2.20. Autocorrelation function of electricity supply data Tsentralna mine on UPP (2 transformer).

The analysis of the autocorrelation function shows that the electricity consumption is practically independent of each other, that is, it is white noise. As a result, the mathematical model of the stochastic time series takes the form

$$p_i = 126.6 + a_i \quad (i = 1,2,\dots,15)\,, \tag{2.85}$$

where $\bar{a} = 0$, $\sigma_a^2 = 3229.6$.

Similarly, an analysis of the stochasticity of the production time series is carried out. In the table 2.11, its average and variance are presented in the last lines

$$\bar{v} = 400.1 \text{ тони}, \quad D[V] = 39252.8 \text{ tons}^2. \tag{2.86}$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.43)

$$\rho_k = \frac{1}{(15-1)\cdot 39252.8}\sum_{i=1}^{15-k} (v_i - 400.1)(v_{i+k} - 400.1). \tag{2.87}$$

The first 4 values of sample autocorrelation are given in the table. 2.13 and shown in fig. 2.21.

Table 2.13

Value of sample autocorrelation

k	0	1	2	3	4
ρ_k	1	0.458	0.336	-0.304	-0.244

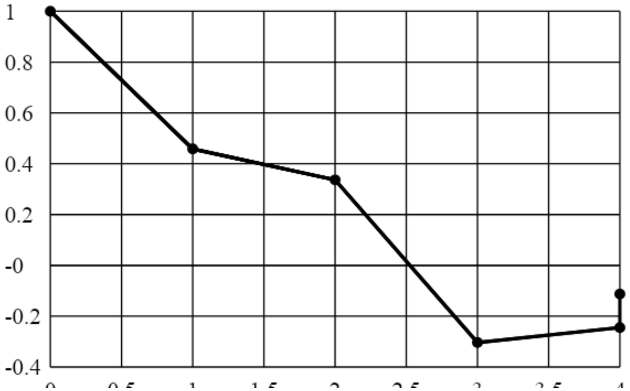

Figure 2.21. Autocorrelation function of data on the production of Tsentralna mine on UPP (2 transformer).

The analysis of the autocorrelation function is characterized by a sign-changing correlation with a tendency to decay as the delay increases. Thus, it can be assumed that there is a first-order autoregressive process, which has the form

$$v_i = 400.1 + 0.458 \cdot (v_{i-1} - 400.1) + a_i \ . \qquad (2.88)$$

where $\bar{a} = 0$.

Next, we conduct calculation studies for the Saksagan mine UPP 10 (transformer 1).

In the table 2.14 presents relevant data.

Table 2.14

Calculation and analytical table of the Saksagan mine UPP 10 (transformer 1)

№	p_i, **kWh**	v_i, **tons**	p_i^2	$v_i \cdot p_i$	**Model** $v_{м,i} = k_0 \cdot p_i$	v_i^2	$(v_{м\,i} - v_i)^2$
1	179.7	592	32292.09	106382.4	487.3464	350464	10952.38
2	184.1	840	33892.81	154644	499.2792	705600	116090.7
3	152.4	704	23225.76	107289.6	413.3088	495616	84501.37
4	190.8	688	36404.64	131270.4	517.4496	473344	29087.44
5	216.2	896	46742.44	193715.2	586.3344	802816	95892.78
6	229.8	800	52808.04	183840	623.2176	640000	31252.02
7	290	888	84100	257520	786.48	788544	10306.31
8	526.2	704	276886.4	370444.8	1427.054	495616	522807.7

9	219.7	784	48268.09	172244.8	595.8264	614656	35409.3
10	200.7	768	40280.49	154137.6	544.2984	589824	50042.41
11	221.6	424	49106.56	93958.4	600.9792	179776	31321.64
12	286.9	912	82311.61	261652.8	778.0728	831744	17936.49
Average	241.5083	750					
Dispersion	9673.061	19818.18					
Amount			806319	2187100		6968000	1035600

According to the data given in the last line of the table. 2.14, using formula (1.55) we find

$$k_0 = \frac{2187100}{806319} = 2.712. \qquad (2.89)$$

The correlation coefficient is found by formula (2.53), according to the data in the last line of the table. 2.14,

$$r = \sqrt{1 - \frac{\sum_{i=1}^{12} \quad (v_i - 2.712 \cdot p_i)^2}{\sum_{i=1}^{12} \quad v_i^2}} = \sqrt{1 - \frac{1035600}{6968000}} = 0.923. \quad (2.90)$$

According to the Chaddock scale, the value of the correlation coefficient (2.60) indicates a high relationship between variables, that is, a mathematical model

$$v_{\text{м}} = 2.712 \cdot p \qquad (2.91)$$

is adequate.

In fig. 2.22 and 2.23 present graphs of the data in the table. 2.14.

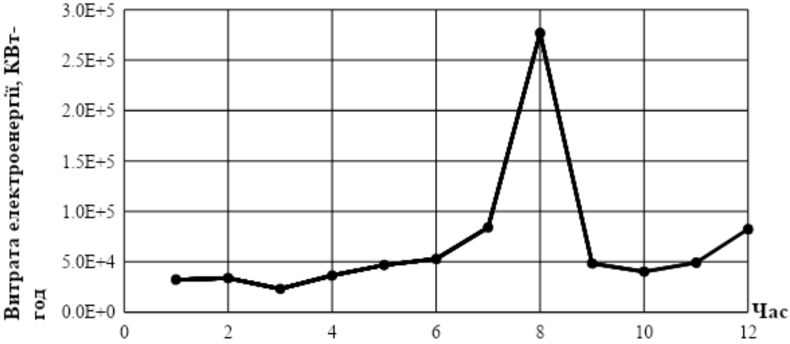

Figure 2.21. Graph of the dependence of the amount of electricity supply on time Saksagan mine UPP 10 (transformer 1)

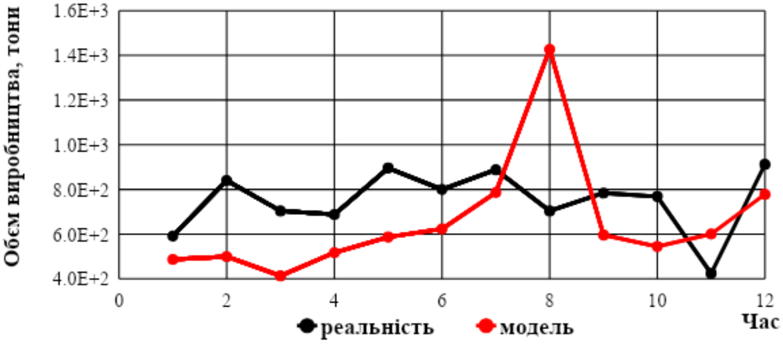

Figure 2.22. Graph of dependence of production and its model on time Saksagan mine UPP 10 (transformer 1)

In fig. 2.22 graphs of dependence of production and its model on time are presented in black and red colors. The analysis of the presented graphs confirms the results about the adequacy of the mathematical model, which were obtained analytically.

Next, we examine the stochasticity of the time series formed by the value of the electricity supply and the volume of production.

Analysis of the graph of the dependence of electricity on time, which is presented in fig. 2.21, indicates its stochasticity. In the table 2.14, its average and variance are presented in the last lines

$$\bar{p} = 241.5 \text{ КВт-год}, \qquad D[P] = 9673.1 \text{ kWh}^2 \qquad (2.92)$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.43)

$$\rho_k = \frac{1}{(12-1)\cdot 9673.1}\sum_{i=1}^{12-k} (p_i - 241.5)(p_{i+k} - 241.5). \quad (2.93)$$

The first 4 values of sample autocorrelation are given in the table. 2.15 and shown in fig. 2.23.

Table 2.15

Value of sample autocorrelation

k	0	1	2	3	4
ρ_k	1	-0.0071	-0.3176	-0.267	-0.106

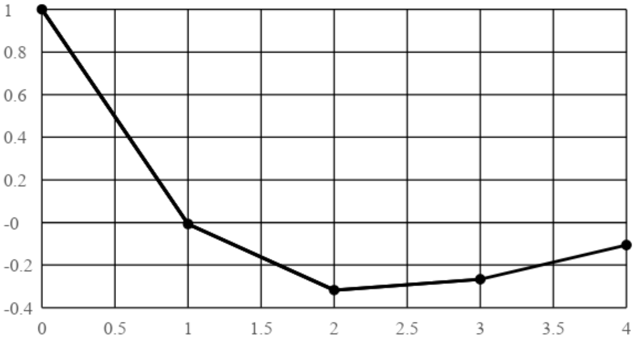

Figure 2.23 Autocorrelation function of electricity supply data Saksagan mine (transformer 1)

The analysis of the autocorrelation function shows that the electricity consumption is practically independent of each other, that is, it is white noise. As a result, the mathematical model of the stochastic time series takes the form

$$p_i = 241.5 + a_i, \quad (i = 1,2,\ldots,12), \tag{2.94}$$

where $\bar{a} = 0, \sigma_a^2 = 9673.1$.

Similarly, an analysis of the stochasticity of the time series of production volume values is carried out. In the table 2.14, its average and variance are presented in the last lines

$$\bar{v} = 750 \text{ тони}, \quad D[V] = 19818.2 \text{ tons}^2. \tag{2.95}$$

To fully characterize the time series, it is necessary to establish a relationship between its members, that is, to calculate the autocorrelation function according to formula (2.43)

$$\rho_k = \frac{1}{(12-1)\cdot 19818/2} \sum_{i=1}^{12-k} (v_i - 750)(v_{i+k} - 750). \tag{2.96}$$

The first 4 values of sample autocorrelation are given in the table. 2.16 and shown in fig. 2.24

Table 2.16

Value of sample autocorrelation

k	0	1	2	3	4
ρ_k	1	-0.361	-0.015	0.147	-0.592

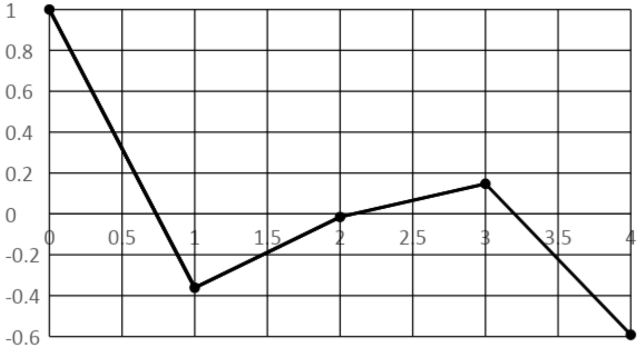

Figure 2.24. Autocorrelation function of Saksagan mine production data (transformer 1)

The analysis of the autocorrelation function is characterized by a correlation with a tendency to decay as the delay increases. Thus, it can be assumed that there is a first-order autoregressive process, which has the form

$$v_i = 750 - 0.361 \cdot (v_{i-1} - 750) + a_i, \tag{2.97}$$

where $\bar{a} = 0$.

Thus, a study of data on the supply of electric energy and the corresponding production volumes at the mines of Kryvbas, namely Artem mine, Tsentralna mine, Saksagan mine, was conducted. Their stochasticity has been proven, corresponding models of the electricity supply system - production for each mine have been built.

2.3 Modeling of the power consumption efficiency of ore extraction devices

The iron ore industry occupies an important place in the economy of many countries. In the world, there is a constant competition for iron ore raw material sales markets. The depths of mining iron ore raw materials have been increasing over the years, which logically entails an increase in the cost of mining this type of mineral. Meanwhile, a feature of iron ore enterprises is their significant energy intensity. It should be noted that more than 30% of the cost of mining iron ore raw materials by modern enterprises with underground mining methods is energy costs, where, in turn, the share of electrical energy is 90% [11]. Today, it is not enough to be limited only to the control of the level of electricity consumption - it is necessary to manage this process. At the same time, the control system should respond adaptively and preventively to the occurrence of relevant disturbing factors in the technology of changing the modes of operation of electric receivers, which for the conditions of iron ore enterprises are stationary installations.

Research results [12] indicate the presence of many alternatives regarding approaches to increase the energy efficiency of mining enterprises. But in these studies, the approach was limited only to the level of selection of structures of power supply systems of underground mining enterprises. Therefore, taking into account new temporary trends, the problem of the need to manage energy flows of mining enterprises was formed and considered in [13]. At the same time, specific solutions were lacking in these studies. Deterioration of technological conditions with an increase in the depth of mining of iron ore raw materials puts the problem of the need to increase the energy efficiency of mining iron ore raw materials to a new level of search. This is additionally confirmed by the fact that the majority of known studies [4] were conducted for the conditions of mining iron ore raw materials at depths of up to 1000 m. Nowadays, these marks have already crossed the boundaries of 1500–2100 m. It is clear that the amount of electricity consumption at such depths, and therefore the level of influence on the general indicators of the production cost of iron ore raw materials has grown and will continue to grow. All this allows us to state that in modern conditions it is reasonable to evaluate the efficiency of electricity consumption of iron ore enterprises with an underground method of mining iron ore raw materials.

Thus, there is currently an urgent need to develop an assessment of the efficiency of electricity consumption of iron ore enterprises with an underground method of mining iron ore raw materials. In practical terms, this will allow optimizing the electricity consumption of iron ore enterprises with an underground method of mining iron ore raw materials.

It is considered expedient to organize such a mode of operation of the ore intake device in order to select a given volume of ore mass. At the same time, minimize the cost of electricity consumption, which is spent on taking a given volume of ore mass. Mathematically, the statement of the problem will be written in the following form [15].

Restrictions in the form of the required volume of electricity consumption for the selection of a given volume of ore mass

$$\int_0^T W(t)dt = Q_0 , \tag{2.98}$$

where $W(t)$ - active power of electricity consumed at the central distribution station (CDS) at the moment of time t, KW,

$[0, T]$ - time interval of operation of the ore mass sampling device, hour,

Q_0- the amount of electricity consumption spent on selecting a given volume of ore mass, KWh.

At the same time, the limits of the amount of active power consumed by the CDS must be met,

$$0 \leq W(t) \leq W_{max} , \tag{2.99}$$

where W_{max}-the maximum amount of active power consumed by the CDS, KW.

The minimization of the cost of electricity consumption, which is spent on the extraction of a given volume of ore mass, is formulated as the task of minimizing the functional of the active power of electricity, $W(t)$ that is consumed, for the allocated time interval $[0, T]$

$$Z = \int_0^T c(t)W(t)dt \to \min_W , \tag{2.99}$$

where $c(t)$ – cost of active power of electricity depending on time, monetary unit/KW.

Thus, conditions (2.97), (2.87) and (2.99) determine the mathematical statement of the problem of minimizing the cost of electricity under the condition of a given amount of ore mass intake.

Let's consider the solution of the considered problem, limiting ourselves to the condition that the cost of the active power of electricity depending on time acquires only two values, that is, it is a piecewise-constant function. One value (smaller) refers to the night time, the second value (larger) refers to the daytime operation of the ore mass intake device. In fig. 2.25 presents a high-quality graphical representation of the considered dependence of the cost of the active power of electricity on time.

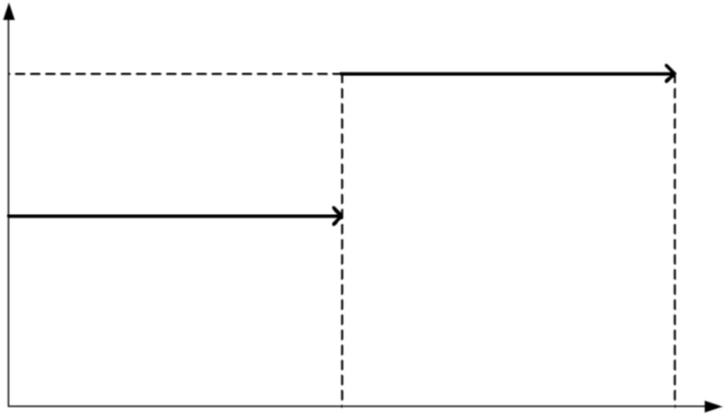

Figure 2.25. Dependence of the value of the active power of electricity on time (c_1 - the value of the active power of electricity at night, i.e. at the interval $[0, t_1]$, c_2 - the value of the active power of electricity during the day, i.e. at the interval $[t_1, T]$)

According to the schedule presented in fig. 2.25, analytically, the function of the cost of the active power of electricity depending on the time of day can be represented by the formula

$$c(t) = \{c_1, \quad 0 \le t < t_1 \; c_2, \quad t_1 < t \le T \; . \qquad (2.100)$$

To solve the problem (2.97), (2.98), (2.99) we will use the form of the function (2.100). Using the linearity of the integral, we find

$$\int_0^T \quad c(t)W(t)dt = c_1 \int_0^{t_1} \quad W(t)dt + c_2 \int_{t_1}^T \quad W(t)dt. \qquad (2.101)$$

Let's introduce a notation

$$Q_1 = \int_0^{t_1} \quad W(t)dt \; , \; Q_2 = \int_{t_1}^T \quad W(t)dt \; , \qquad (2.102)$$

where Q_1, Q_2 – electricity consumption in time sections, where the cost of electricity is c_1 and c_2, respectively.

Then the functional (2.99) taking into account (2.102) will be written as follows

$$Z = Q_1 \cdot c_1 + Q_2 \cdot \quad {}_2 \; . \qquad (2.103)$$

In turn, the constraint (2.96) can be written in the form

$$\int_0^T \quad W(t)dt = \int_0^{t_1} \quad W(t)dt + \int_{t_1}^T \quad W(t)dt,$$

or, taking (2.97) and (2.103) into account,

$$Q_1 + Q_2 = Q_0. \tag{2.104}$$

Constraint (2.98) on the first time interval by integration will be presented in the form

$$0 \le \int_0^{t_1} \quad W(t)dt \le \int_0^{t_1 \int} \quad W_{max}. \tag{2.105}$$

According to (2.102), the inequality (2.105) can be written in the form

$$0 \le Q_1 \le \int_0^{t_1 \int} \quad W_{max}\ . \tag{2.106}$$

Calculating the integral in the right-hand side of inequality (2.106), we finally find the limit of electricity consumption in the time section, where the cost of electricity c_1

$$0 \le Q_1 \le \underline{Q_1}\ , \tag{2.107}$$

where $\underline{Q_1} = W1_{max}$.

Limitation (2.98) on the second time interval $[t_1; T]$ by integration will be presented in the form

$$0 \le \int_{t_1}^{T} \quad W(t)dt \le \int_{t_1}^{T \int} \quad W_{max}. \tag{2.108}$$

According to (2.102), the inequality (2.108) after integration will be written in the form

$$0 \le Q_2 \le \underline{Q_2}, \tag{2.109}$$

where $\underline{Q_2} = W1_{max}$.

Taking into account the obtained results, the energy consumption minimization task (2.97), (2.98), (2.99) taking into account (2.107) and (2.108) is written in the form

$$Z = \mathrm{c}_1 Q_1 + c_2 Q_2 \to \min_{Q_1, Q_2}, \tag{2.110}$$

$$Q_1 + Q_2 = Q_0, \tag{2.111}$$

$$0 \le Q_1 \le \underline{Q_1}, \tag{2.112}$$

$$0 \le Q_2 \le \underline{Q_2}. \tag{2.113}$$

Analysis of the problem (2.110), ..., (2.113) shows that this problem belongs to linear programming problems [16]. Such a task can be solved both geometrically and analytically.

Before solving problems (2.110), ..., (2.113), it is necessary to determine the conditions under which the solution exists. This applies to constraints (2.111), (2.112) and (2.113). Problem (2.110),...,(2.113) is defined by two variables Q_1 and Q_2, so it is convenient to solve it geometrically. For this, we will use the representation of constraints (2.111), (2.112) and (2.113) on the plane in coordinates Q_1 and Q_2.

The inner rectangle in fig. 2.26 defines the domain of constraints (2.12) and (2.13). In turn, the segment of the straight line passing through the points (0; Q_0) and (Q_0;0) determines the constraint (2.15). Analysis of the location of restrictions in fig. 1.26 shows that in this case the problem (2.110),...,(2.113) has no solution, because the line segment that corresponds to the constraint (2.111) does not cross the rectangular region formed by the constraints (2.121) and (2.113) .

The condition for the existence of a solution to the given problem can be defined as the existence of a non-zero distance between the corner point $M(\bar{Q}_1; \bar{Q}_2)$ and the line passing through the points (Q_0;0) and (0; Q_0), that is, by the equation given in the form

$$(l)\colon Q_2 + Q_1 = Q_0. \qquad (2.114)$$

Analytically, using the methods of analytical geometry, this condition can be written as the deviation of the point $M(\bar{Q}_1; \bar{Q}_2)$ from the straight line l

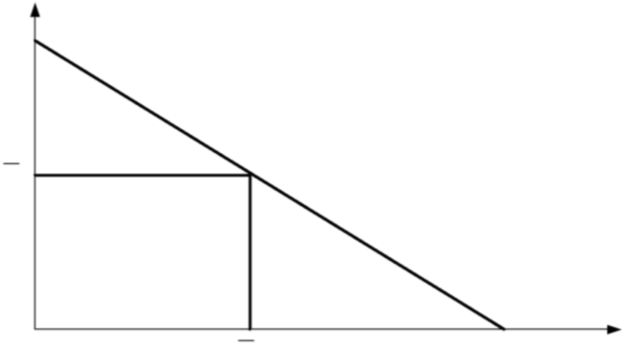

Figure 2.26 Graphic representation of constraints (2.111), (2.112) and (2.113) in the absence of a solution

$$\rho(M; l) = \frac{\bar{Q}_2 + \bar{Q}_1 - Q_0}{\sqrt{2}} < 0 ,$$

or, more briefly,

$$\bar{Q}_2 + \bar{Q}_1 - Q_0 < 0 . \qquad (2.115)$$

Considering (2.107) and (2.109), inequality (2.115) can be written in the form

$$W11_{0_{max_{max}}},$$

or, after algebraic transformations,

$$W \frac{Q_0}{T}_{max} \quad . \tag{2.116}$$

Thus, condition (2.116) determines the condition for solving problem (2.110),...,(2.113).

Let us consider the geometric solution of the problem (2.110),...,(2.113) under the condition of the existence of the solution, that is, the fulfillment of the condition

$$W \frac{Q_0}{T}_{max} \quad . \tag{2.117}$$

In fig. 2.27 presents a graphic representation of the situation with the existence of a solution. Thicker lines highlight the area of possible existence of a solution. At the same time, taking into account the constraint (2.111) in the form of equality, it can be asserted that the solution must be on the segment $[M_1 M_2]$. To find a specific value, we use condition (2.110). The direction of the fastest growth of the functional Z is determined by its gradient, which is written in the form

$$\text{grad Z} = \left(\frac{\partial Z}{\partial Q_1}; \frac{\partial Z}{\partial Q_2}\right). \tag{2.118}$$

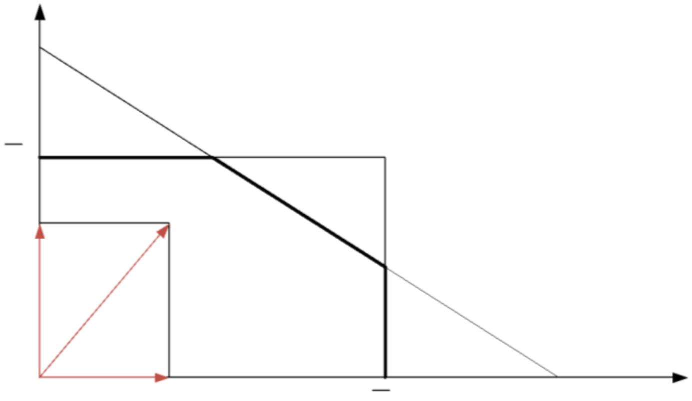

Figure 2.27. Graphic representation of constraints (2.111), (2.112) and (2.113) in the presence of a solution

Considering the specific form of the functional Z, we find according to (2.117)

$$\text{grad } Z = (c_1, c_2). \qquad (2.119)$$

In fig. 2.27 shows, in accordance with (2.119), the direction of the Z gradient under the condition that $c_1 < c_2$ (this corresponds to the ratio of the cost of electricity at night and during the day). Moving in the direction opposite to the direction of the gradient Z, we find the smallest value of the functional Z. This value will be reached at the point

$$M_2\ (\underline{Q}_1; Q_0 - \bar{Q}_1).$$

At the same time, the minimum value of the target function will be

(2.120)

Let us consider the analytical solution under the condition that the solution exists, that is, condition (2.120) is fulfilled. For this, let's go to one variable, using condition (2.111),

$$Q_2 = Q_0 - Q_1. \qquad (2.121)$$

As a result, the objective function (2.110) will be written in the form

$$Z = c_1 Q_1 + c_2 (Q_0 - Q_1) \to \min_{Q_1},$$

or after regrouping

$$Z = c_2 \cdot Q_0 - (c_2 - c_1) \cdot Q_1 \to \min_{Q_1}. \qquad (2.122)$$

In turn, condition (2.113) will take the form

$$0 \le Q_0 - Q_1 \le \overline{Q_2},$$

or, after algebraic transformations

$$Q_0 - \overline{Q_2} \le Q_1 \le Q_0. \qquad (2.123)$$

Taking into account (2.122) and (2.123), the task of minimizing energy consumption will be written in the form

$$Z = c_2 Q_0 - (c_2 - c_1) \cdot Q_1 \to \min_{Q_1}, \qquad (2.124)$$

$$0 \le Q_1 \le \underline{Q_1}, \qquad (2.125)$$

$$Q_0 - \underline{Q_2} \le Q_1 \le Q_0. \qquad (2.126)$$

Since the objective function Z depends linearly on the variable Q_1 and $c_2 > c_1$, the minimum value is reached on the right boundary of the variable Q_1, that is, the optimal value

$$\hat{Q}_1 = \bar{Q}_1. \qquad (2.127)$$

At the same time, according to (2.120),

$$\hat{Q}_2 = Q_0 - \bar{Q}_1. \qquad (2.128)$$

The obtained result coincides with the previously found geometric path. It should be emphasized that as a result of solving the problem (2.110), (2.111), (2.112) the optimal electricity consumption for the given time intervals determined by its differentiated cost, i.e.

$$\int_0^{t_1} W(t)dt = \hat{Q}_1, \tag{2.129}$$

$$\int_0^{t_1} W(t)dt = \hat{Q}_2 \; . \tag{2.130}$$

According to (2.130), we find the average value of the active power during the time interval $[0; t_1]$, where the cost of electricity c_1,

$$\underline{W_1} = \frac{\hat{Q}_1}{t_1}. \tag{2.131}$$

Considering (2.126), formula (2.131) can be written in the form

$$\bar{W}_1 = \frac{\int_0^{t_1} W(t)dt}{t_1} = \frac{W1_{max}}{t_1},$$

i.e

$$\bar{W}_1 = W_{max} \tag{2.132}$$

In turn, according to (2.130), we find the average value of the active power during the time interval $[t_1; T]$, where the cost of electricity is c_2,

$$\underline{W_2} = \frac{\hat{Q}_2}{T - t_1}.$$

Considering (2.127), we can write

$$\underline{W_2} = \frac{Q_0 - \bar{Q}_1}{T - t_1} = \frac{Q_0 - W1_{max}}{T - t_1}. \tag{2.133}$$

Considering (2.132), the minimum value of the functional (2.134) consistently takes the form

$$Z_{\min} = c_2 Q_0 + (c_1 - c_2) \cdot \hat{Q}_1,$$

$$Z_{\min} = c_2 Q_0 + (c_1 - c_2) \cdot \bar{Q}_1,$$

$$Z_{\min} = c_2 Q_0 + (c_1 - c_2) W_{\max} \cdot t_1 . \tag{2.134}$$

Further research requires the involvement of statistical data on electricity consumption at individual enterprises with underground mining of iron ore raw materials to confirm the obtained results.

As an example, for the sake of clarity, we will cite a study of electricity consumption by iron ore enterprises of the private joint-stock company "Kryvorizk Iron Ore Combine", Ukraine. Power-generating enterprises (oblenergo), striving for an ideal daily equalization of electricity "production-consumption" volumes, stimulate consumers. The price policy of generating enterprises in relation to electricity consumers corresponds to the time intervals that form the zonal tariffs for electricity consumption. In the table 2.17 provides relevant data for two-zone electricity consumption tariffs.

Analysis of table data. 2.17 shows that the price of consumed electricity changes during the day.

Table 2.17

Zone tariffs for electricity consumption

Zonal tariffs	Price, UAH/kW·h	Tariff limits
$c_{н}$ (night)	0,96	from 11pm to 7am
$c_{д}$ (day)	2,20	from 7am to 11pm

The highest price of consumed electricity is observed during the day, which, of course, is associated with a large number of electricity consumers and causes a shortage of electricity. On the contrary, the price of consumed electricity is the lowest at night, which is also explained by the number of working electricity consumers and the availability of excess electricity. Thus, enterprises in general and iron ore enterprises in particular face the problem of solving the dual problem of distributing electricity consumption in hours of the day while simultaneously ensuring the continuity of the technology of production processes.

In fig. 2.28 presents the daily schedule of electricity consumption at the analyzed enterprise

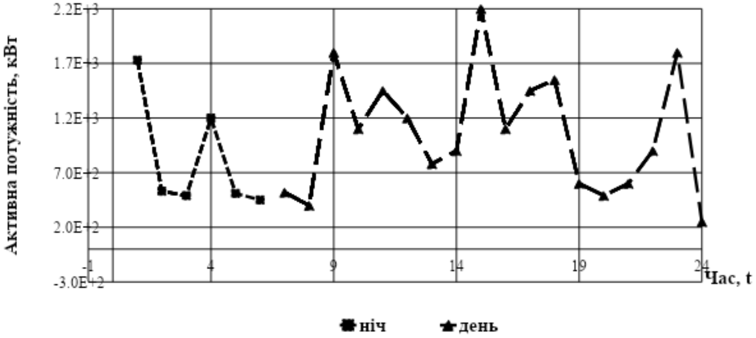

Figure 2.28 Daily schedule of electricity consumption by an iron ore enterprise

We calculate the integral characteristics of real electricity consumption, according to the graph in Fig. 2.28. Electricity consumption during the day is the amount

$$Q_0 = \int_0^{24} W(t)dt = 24000 \text{ kWh}. \tag{2.135}$$

According to (2.117), we determine the condition for the solution of problem (2.110),...,(2.113)

$$W_{max} \geq \frac{Q_0}{T} = \frac{24000}{24} = 1000 \text{ kW}. \tag{2.136}$$

According to Fig. 2.28, it can be assumed that

$$W_{max}\text{kW}. \tag{2.137}$$

Next, we will calculate the cost of electricity consumption, according to the form of the functional (2.103). Preliminarily, we find the electricity consumption for the "night" and "day" zone tariffs, respectively,

$$Q_{н} = \int_1^{7} W(t)dt = 5160 \text{ kWh}, \tag{2.138}$$

$$Q_{д} = \int_7^{24} W(t)dt = 18840 \text{ kWh}. \tag{2.139}$$

We substitute the obtained results (2.138) and (2.139) into the formula (2.103) and, using the data in the table. 2.17, we find the total costs of electricity consumption per day in hryvnias

$$Z = c_{н} \cdot Q_{н} + с_{д} \cdot Q_{д} = 0{,}96 \cdot 5160 + 2{,}20 \cdot 18840 = 4953{,}6 + 41448 = \\ = 46401{,}6 \text{ hrn}. \tag{2.140}$$

According to (2.134), we find the minimum amount of total costs for electricity consumption per day in hryvnias

$$Z_{min} = 0.96 \times 15400 + 2.2 \times 8600 = 33704 \text{ hrn}. \tag{2.141}$$

The application of the algorithm for minimizing the levels of electricity consumption of iron ore enterprises, which is represented by formulas (2.110)–(2.117), showed that in the specified types of enterprises there is a corresponding reserve for optimizing the levels of electricity consumption, which is based on the effective consideration of tariffs. This can be confirmed by comparing the actual costs with the optimal costs of electricity consumption for the example that was considered above. Given (2.138) and (2.139), we find the value of the relative decrease in electricity consumption of the enterprise during the day

$$\frac{Z - Z_{min}}{Z} \cdot 100\% \approx 27.4\ \%. \tag{2.142}$$

Thus, the electricity consumption of stationary installations of one iron ore mine during the day can be reduced by 27.4%, while preserving the total amount of electricity consumption.

The peculiarity of the method of solving the problem, which is recommended, is that the dependence of the electricity price on time is given in the form of a piecewise-constant function. As a result, the price of electricity is given by a piecewise-constant function with two values.

In comparison with the existing practice of assessing EE levels, the foundation has been created to ensure the possibility of applying analytical methods for the analysis of cost-target characteristics of electricity consumption levels at mining enterprises. In this case, the limitations are determined by the power of electricity, which is determined by the characteristics of the object under study.

REFERENCES

1. Babets, E. K. Research of technical and economic indicators of mining enterprises of Ukraine and their efficiency in the conditions of changing conditions of the world market of iron ore raw materials [Text]: monograph / E. K. Babets, I. E. Melnykova, Ya. Grebenyuk, S. P. Lobov; NDRI DVNZ "KNU". - Kryvyi Rih: ed. R. A. Kozlov, 2015. – 391 p.
2. Babets, E. K. Collection of technical and economic indicators of mining enterprises of Ukraine in 2009–2010: Analysis of the world situation of the mining industry market 2004–2011 [Text]: monograph / E. K. Babets, L. A Shtanko, V. A. Salganik, I. E. Melnikova - Kryvyi Rih: Publishing House, 2011. – 329 p.
3. Shidlovsky, A. K. Geoeconomics and geopolitics of Ukraine [Text]: monograph / A. K. Shidlovsky, H. Kh. Pivniak, M. V. Rogoza. - Dnipro: National Mining University, 2007. – 282 p.
4. Sinchuk, O. N. The potential of electrical energy efficiency and ways of its realization at productions with underground methods of extraction of iron ore raw materials [Text]: monograph / O.M. Sinchuk, I.O. Sinchuk, E.S. Guzov, O.M. Yalova, S.M. Boyko; edited by Dr. Tech. Sciences, Professor O.M. Sinchuk // Kremenchuk: Ed. PP Shcherbatykh A.V., 2015. – 296 p.
5. Khorolskyi, V.P. Integrated intellectual management of technological processes in the economic systems of enterprises of the mining and metallurgical complex [Text]: monograph/ V.P. Khorolsky - Dnipro: January, 2008. – 448 p.
6. https://uk.wikipedia.org/wiki/Стохастичність
7. https://uk.wikipedia.org/wiki/Кореляційна_функція
8. Novytskyi, I.V. Random processes. [Text], study guide / I.V. Novytskyi, S.A. Us. - D.: National Mining University, 2011. – 125 p.
9. Sedov, L.I. Methods of similarity and dimensionality in mechanics / L.I. Sedov. - M: Science, 1987. – 430 p.
10. Kamornikov, S.F. Econometrics. [Text], study guide/ S.F. Kamornikov, S.S. Kamornikov. – K.: Integration, 2012. – 262 p.
11. Synchuk I.O., Guzov E.S., Yalovaya A.N., Boyko S.N.; under the editorship of Dr. Tech. Sciences, professor O.N. Synchuk Electrical efficiency of production with underground mining methods. / Monograph Izd. LAP LAMBERT Academic Publishing, 2016. 351 p.
12. Hladylin L.V. Osnovy elektrosnabzheniya hornykh predpriyatiya M.:

Nedra, 1980. 327 p.

13. Prakhovnyk A.V., Rosen V.P., Degtyarev V.V. Energy-saving power supply modes of mining enterprises. M.: Nedra, 1985. 232 p.
14. Shchutsky V.Y., Lyakhomsky A.V., Egorov D.A. Increasing the accuracy of determining the calculated loads of electrical installations of polymetallic mines / Izv. University of Electromechanics, 1989, No. 3, pp. 109-112.
15. Yehorshyn O.O., Malyarets L.M. Mathematical programming. Ch.: VD "INZHEK", 2006. 384 p.
16. Lavrinenko N.M., Latynin S.M., Fortuna V.V., Beskrovnyi O.I. Basics of economic and mathematical modeling. Lviv: "Magnolia 2006", 2010. 540 p.

Kobeliatskyi Danyil Vitaliiovych

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