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FUNDAMENTALS OF INTEGRATING SMART TECHNOLOGIES FOR CONTROLLING POWER SYSTEMS AT IRON ORE UNDERGROUND MINING ENTERPRISES

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S 38 **Fundamentals of integrating smart technologies for controlling power systems at iron ore underground mining enterprises**/Monograph/ I. Sinchuk, K. Budnikov, R. Krasnopolsky. – Warsaw: iScience Sp. z.o.o. – 2021. – 123 s.

The monograph presents an analysis of mining enterprises' functioning, which reveals stable irregularity of their power consumption in different periods – days, weeks, months. The largest fluctuations are observed during 24 hours. Yet, the maximum consumption occurs at non-economic hours, when electricity tariffs are the highest. It is proved that a shift of operation modes of electricity consumers to 24-hour economic zones looks extremely commonplace and does not give expected efficiency.

Comprehensive studies of power engineering on the example of Ukrainian iron ore mines and their mathematical modelling enable the authors to develop a methodology for creating a basic framework to build a smart (automated) control system of power flows between consumers-controllers of electricity.

The economic and energy components of developing the Automated Control System (ACS) of electric power consumption are studied with proposals for their practical implementation at mining enterprises. The analysis shows power consumption of iron ore production aimed at redistribution of power flows between receivers-controllers in hours of day for both three-tariff and two-tariff pricing options for consumed electric power within the current legal framework. Unclear and/or incomplete information on the amount of extracted raw materials, water drainage and ventilation conditions application of Fuzzy logic to conducting the studies. The number of control actions is determined by correlation between controlling and controlled parameters of basic technological components of mining.

The mentioned approaches will allow implementation of automated control over mine power consumption in real time and optimization of power costs, which will result in significant reduction of mining enterprises' expenditures for power consumed in the structure of mining costs.

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(1922 – 2022)

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(1961 – 2021)

CONTENTS

LIST OF ABBRIVIATIONS

GZK	–	mining and beneficiation plant
PJSC	–	private joint stock company;
KZRK	–	Kryvyi Rih iron ore works
MMK	–	PJSC Ilych Iron and Steel Works of Mariupol
u/m	–	underground mine
ACS	–	automated control system
GDP	–	gross domestic product
CSP	–	crushing and sorting plant
MSDS	–	main step-down substation
SUS	–	site underground substation
EEPL	–	energy-efficient production level
FLT	–	Fuzzy Logic Toolbox
ASPCC	–	automated system for power consumption control

INTRODUCTION

Ukraine is a unique country in terms of available minerals. Occupying approximately 0.03% of the total land area of our planet, the country is mining 5% of world mineral resources [1-2]. Our state is among top ten producers of mineral raw materials in the world. World-famous manganese deposits of Ukraine make up 80% of world production, those of iron ore – 14%.

Due to this and a number of other factors, including historical and political ones, Ukraine is currently among those countries whose economy is developing on the basis of raw materials. This mainly involves production and processing of iron ore materials with their annual export to 12-15 foreign countries, this enabling the country's foreign exchange replenishment by over 60%.

In Ukraine, iron ore mining is carried out by both open-pit/surface (followed by raw ore beneficiation at mining and beneficiation plants) and underground mining methods. Over the past 5 years, there has been a tendency of non-reduction and even periodic increase in iron ore production by both open-pit and underground mining methods [2-4].

Currently, in Ukraine, iron ore open-pit (surface) mining is higher than the underground one in terms of production volume. However, commercial iron ore underground mining is increasing and, thereby, the previous dominant status of this mining method is being restored [4, 5]. There are a number of objective factors determining this trend, including the fact that the underground method, unlike the open-pit (surface) one, is characterized by a more sustainable influence on the environment and higher iron content in raw ore which almost eliminates the need for energy- and time-consuming beneficiation of ore mined.

Over 30% of total iron ore in Ukraine is mined by underground methods. This and a number of other important factors make underground mining enterprises quite promising in terms of iron ore production. Meanwhile, iron ore mining costs annually increase, both for objective (increased mining depth exceeding 1500m, with an outlook for 2000m-2300m [43-44]) and some subjective reasons [4].

For mining enterprises, far from being positive is the fact that in recent years the global iron ore market has been severely depressed, and prices for raw materials are negatively fluctuating by nature [3, 4].

To illustrate this, let us consider the fact that the maximum price for iron ore was fixed in 2011 and amounted to 191.7$/t; while the minimum price for this raw material was fixed in 1988 at 10.51$/t [4].

Gaps between peaks of price changes from maximum to minimum values and vice versa make about 30 years. Each peak consisted of a ten-year rise followed by a 5-year collapse which turned into a relatively smooth decline of another 15 years. The highest price peaks were recorded in 1917, 1951, 1980 and 2011, while the lowest ones occurred in 1931, 1971, and 2002. If the current cycle repeats the previous ones, the next minimum cycle, or a turning point, should be expected in 2030, if nothing extraordinary happens so far.

As a currently observed extraordinary fact of such a behaviour, there is a tendency of iron ore production costs increasing at domestic mining enterprises [4]. Thus, since 2013, the production cost has grown by almost 60%. Such a crisis in the Ukrainian mining and steel industry as today has been unprecedented in recent 15-24 years [2].

The above situation is a sign of an approaching economic decline for Ukrainian iron ore mining enterprises, as in the competitiveness hierarchy they may lose their worthy place among the top ten iron ore producers with corresponding consequences of this undesirable phenomenon for both macro- and microeconomics of the nation.

Constant increase in prices for energy including electricity consumed by enterprises is one of the negatively progressive factors that adds to production costs growth [2-5]. It is the electricity segment that is the main driving factor here indicating low energy efficiency of iron ore enterprises.

According to Prof. Kaplenko [36], reduction of power consumption by 1 kW*h/t of iron ore materials will reduce production costs by 10.2 UAH/t, i.e. for a mine with a typical iron ore production of 4-5Mt/year the savings will make about 50M UAH in 2018 and this is without taking into account the constant power prices increase.

The aforementioned amount can and should be an incentive to increase miners' wages by almost 4.2M UAH per month or be invested in production modernization.

This dependence is explained by the fact that iron ore mining enterprises, as well as the mining and metallurgical industry as a whole, are energy-intensive [6-13]. Analysis of the prime cost components for underground iron ore mining indicates that power costs constitute about 30% of total ones. In turn, electricity covers over 95% of these costs. Besides the problem of electric energy efficiency due to installed significant power capacities, underground iron ore mining enterprise's activity is also complicated by great fluctuations in power consumption levels during the day, months, and seasons. Daily variations in power consumption are the largest [14-24].

As it is established in [39, 40], the range of existing fluctuations in daily hours by levels of electricity consumption at Ukrainian iron ore mines on average exceeds 4 multiple values. Such fluctuations are not observed in any other types of industrial enterprises, even including those similar to iron ore mines – coal, shale, salt mining and other types of mines [9, 25-36, 45, 47]. This fact negatively affects power engineering of iron ore mining enterprises.

Mining technology applied to these types of enterprises, which is known [9, 45, 47] to largely determine energy efficiency of iron ore mining and condition this situation as a whole. Taking into account prospects of Ukraine's iron ore industry, it should be noted that in the following 30-50 years no new mining enterprises are going to be built. Therefore, one should not expect introduction of new technologies into mining practices as a way of reducing energy intensity of production of this type of minerals.

The life of operating iron ore mines in Ukraine, as well as their electric power systems, is over 50-60 years [45, 46]. If we take into account the fact that over the past 20-25 years the electric power systems of these enterprises have almost not been upgraded, the reason for their low economic efficiency will be understandable.

Besides, it would be appropriate to note that problems of power engineering at mining enterprises do not end even after their closure or conservation [13-15, 47-130]. This is another important impulse to conduct a timely research into ways of increasing electric energy efficiency of these enterprises within a comprehensive direction of the search goal.

Researches conducted for coal mines [71-73] and other types of mining and industrial enterprises [47-77] are the closest to investigations of the given direction. Meanwhile, the difference in mining technologies at coal and iron ore mines, and especially at other industrial enterprises, does not allow us to transfer research results even in the first approximation from "coal" to "ore".

In addition to this statement, it should be noted that, in particular, final results of well-known studies do not include scientifically substantiated modern methods to develop design-forecasting programmes and improve energy efficiency of mineral mining aimed at identifying feasible energy-efficient measures to implement a targeted, extremely possible potential of enhancing the enterprise's energy efficiency.

All this imposes different approaches to formation, and most importantly the level of fulfillment of requirements for both the structures and parameters of power supply systems, and operating modes of electrical equipment, which is decisive, and at the same time the main factor in personalizing the approach to forming such a solution to the problem of increasing energy efficiency to consider special conditions of coal and iron ore mines.

Yet, for both ore and coal and other types of mines, all ways of searching for measures to increase energy efficiency of these types of enterprises are reduced to minimizing the difference between existing and possibly attainable levels.

There is no doubt that at mining enterprises, in one way or another, certain measures are being implemented to improve energy efficiency. These measures are rather characterized as trivial, e.g. replacing inefficient electric drives with efficient ones, installing filter-separating devices, etc. There is a certain positive effect of such measures. However, according to [45,47], this "positive" is actually leveled by a significant, and more often complete, absorption of the power consumption level achieved due to mining depth increase.

It is logical that the maximum effect of power saving can be achieved under the integrated approach to problem solving. In this direction, it is expedient to build a "roadmap" for implementing certain measures. At the same time, the priority in making a decision should be given to the most efficient measures in a set of solutions. It is also reasonable that without real scientific substantiation, the final positive result with the desired level of efficiency cannot be achieved.

However, when choosing ways to implement energy-efficient measures at operating iron ore mining enterprises, one should actually understand that the objective process implies an increase of power consumption because of growing mining depths, which according to [1–19] annually makes over 1 kW*h/t without taking into account electricity prices. This value covers those parts of energy efficiency segments that can be achieved (or are achieved) through measures such as replacing unadjustable types of electric drives with adjustable ones [9] and a number of other ordinary steps.

Of course, the above in no way question the need and feasibility of implementing these and other measures to improve energy efficiency of iron ore mining. Moreover, it is trivial and quite categorical to state that the maximum effect of increasing electric power efficiency of iron ore mining can be, and will be, achieved only with comprehensive implementation of all possible and affordable to date measures.

In this case, restraining and reducing prices for electricity consumed are primary steps aimed to enhance energy efficiency of iron ore mining enterprises for a short-term investment period.

This statement is also stimulated by the law "On the Electric Power Market in Ukraine" [37], according to which the structure and form of payments between power consumers and suppliers has changed since 2019. Moreover, now to receive power, enterprises should conclude not one, as before, but several separate agreements with two companies – with the power transporter and the power supplier.

At the same time, forms of payment vary among power supplying companies. Nevertheless, the dominant point in paying for electricity consumed is its supplier. The form of payment for the volume of power consumed is based on 24-hour tariffs and in total – more than 700-t during a month.

It is important that the levels of all these tariffs are "floating" and depend on the current state of prices on the domestic power market.

It is reasonable that the ideal final forecast of prices for electricity consumers implies development of "smart" systems of adaptive control depending on hours of the day, where the maximum limits of the minimum price for the consumed kWs of power are possible, using each of the entire range of the above tariffs. On the other hand, unlike the ideal (best) option, it is optimal to establish a dominant lever or dominant levers of each segment (tariffs) and choose the most influential or influenced criterion/criteria that is/are controllable.

Yet, even the a priori vision of such a decision with time constraints of its implementation does not look real. Taking into account the specific weight of each criterion, it is expedient to conduct their preventive ranking and highlight the most significant ones in terms of their influence on formation of the total price for electricity on a daily/monthly basis.

This approach should not include, or rather predict, a potential of increasing the number of criteria of influence and change their priorities while developing the algorithm for managing power supply and consumption.

A positive point among others in terms of efficiency of this tendency is that in the general structure of the energy-intensive power system of underground iron ore mining enterprises, their fullness is based on a limited number of energy-intensive consumers. Consuming 90-95% of the total power of the enterprise, these consumers form the current technology of iron ore mining. In other words, the task of improving energy efficiency of the entire underground iron ore enterprise is solved by redistributing power flows among energy-intensive consumers within the framework of established tariffs.

In modern conditions, it is logical that in relation to electricity as a basic component in formation of iron ore costs, today only to control the levels of electricity consumption is not enough, both for pure economic reasons and from the viewpoint of developing the mining industry itself. Currently, it is necessary to control this process as a set of components of mining technology designated for this type of minerals.

The ACS of power consumption should become an expected result of searching for ways to increase the electric power efficiency of underground iron ore mining enterprises. The structure of the algorithm functioning of the

ACS should provide for forecasting the volume of managerial decisions in this direction.

Continuing this topic, it should be noted that some of the well-known advances in the analyzed research direction look very timid, since their ACS is predicted not as an integral control system of the above complex with the function of controlling the level of power consumption, but only as a subsystem for fixing consumption levels at certain periods of time. In real-time conditions, these are only "elements" of creating an integrated *ACS of electric power consumption*. The authors think that in modern conditions of the industry, this is not enough for solving such a complex and global problem as improving energy efficiency of mining enterprises.

Thus, theoretical substantiation, evaluation and development of methods for ensuring required and possibly affordable energy efficiency aimed at maximum realization of mining enterprises' power potential by developing *the ACS of electric power consumption* for current and designed enterprises of underground iron ore mining not only in Ukraine, but also in other countries are relevant and timely research tasks. To solve them, it is possible to attract investors from different countries, since these problems are of global significance.

SECTION 1
POWER ENGINEERING OF IRON ORE UNDERGROUND MINING ENTERPRISES. STATE AND PROSPECTS

1.1 Iron ore mining and its role in Ukraine's energy strategy

The main task of the state Sustainable Development Strategy "Ukraine-2020" is to enhance energy security and transition to energy-efficient and energy-saving use and consumption of all types of energy resources.

Today, energy security is the cornerstone of the policy in many countries [12, 131, 132]. It is appropriate to note that by 2030, according to the Ministry of Fuel and Energy of Ukraine, the country is going to reduce energy consumption by 12%, including that in metallurgy by 30% [6-8].

In opposition to this, it should be noted that, there was no such a trend in power consumption before 2019. The level of power consumption in 2019 in comparison with that in 2013 did not almost decrease, and in metallurgy, including its raw material base – the mining industry – it did not decrease at all remaining at the level of about 24.5% of the total consumption level.

Meanwhile, reforms in the management system of energy industry enterprises including establishment of technological ties with power consumers have not been completed yet, which leads to constant corruption scandals, extremely nontransparent and inefficient functioning of the *power supplier- power consumer* complex.

Coal, ore mining and metallurgy enterprises are significant and dominant in terms of power consumption with no interaction with generating and distributing power systems so far.

The iron ore industry as the basic component of metallurgical production, consuming almost 45 % of the total power produced plays an important role in many modern economies of the world (including the Ukrainian economy as well). Moreover, it is the iron ore industry that is traditionally considered one of the indicators of the economic state in developed countries of the world. Demand for iron ore is a direct consequence of development, first of all, of material-intensive industries from mechanical engineering to high technologies. In this context, such an indicator, albeit unofficially recognized, looks interesting, as a country's consumption of iron per capita, which, for example, in Japan is about 1000kg, Germany – 510kg, China – 218kg, the Russian Federation – 300kg, Poland – 314kg, Ukraine – 94kg[1].

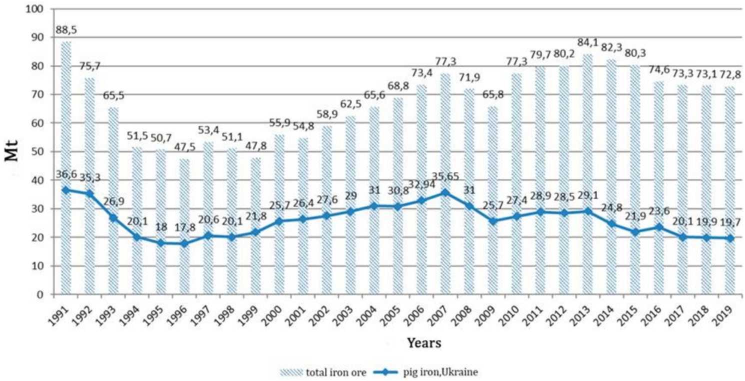


Fig. 1.1 – Pig iron production by metallurgical enterprises of Ukraine and iron ore supply in 1991-2019

According to forecasts, a significant reduction in the volume of world needs for iron and iron ore in the next century cannot be expected (Fig. 1.1). Given the current level of development, these resources will be sufficient for at least another 140 years [4]. According to CAGR forecasts, demand for iron ore materials will be growing until 2035 with an average annual growth rate of 1.5%.

At present, the general situation on the world iron ore market is determined by:

– the trend of increasing iron ore production with its insufficient supply and demand, this fact contributing to higher prices on the wholesale market and causing an increase in prices for iron ore shipment under long-term contracts;

– further strengthening of China's role on the iron ore market as its largest consumer;

– preservation and strengthening of the world leading mining companies' positions on the global market by implementing large-scale investment projects;

[1] In 1980, iron ore consumption per capita in the Ukrainian Soviet Republic (now Ukraine) made 1024kg.

– significant investments of mining and metallurgical companies in modernization and reconstruction of iron ore mining enterprises, expansion of production capacities to produce and process iron ore, construction (modernization) of new mining enterprises;

– introduction or planning of introduction of restrictive measures for iron ore export (Russia, China, Indonesia, India);

– an increase in freight rates due to the insufficient number of vessels, restriction of port capacity in main iron ore exporting countries, including Ukraine;

– a desire of large metallurgical companies to provide themselves with iron ore by participating in iron ore projects abroad, as well as through purchasing available iron ore assets, including those in Ukraine.

On the world iron ore market, the above-mentioned moments of the general situation directly concern Ukraine which is one of the significant players in the global process of availability, production and sale of iron raw materials (Fig. 1.2).

In Ukraine, iron ore mining and production has a long tradition and very good prospects [2, 3, 6].

It should be noted that since the fifth month of 2013, Ukraine has risen and, according to experts, ranks fourth in terms of iron ore exports in the world, being ahead of Canada [3]. At the same time, since 2015, the volume of iron ore production in Ukraine has approached a record positive level for the country in 1990 with a future focus on underground mining, or combined open-pit and underground mining.

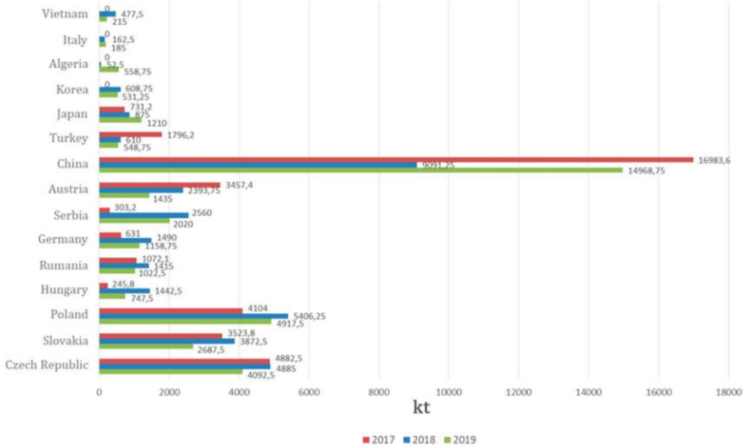


Fig. 1.2 – Geography of Ukraine's iron ore exports in 2017-2019

The Ukrainian raw material base of iron ore mining enterprises possessing 80 prospected deposits, 23 of which are operating (58% of the explored reserves) is sufficient for production of required volumes of these products, for both the state's internal needs and exports for the next 50-100 years.

The raw material base of domestic iron ore mining enterprises includes deposits of ferruginous quartzite and natural-rich ores.

Kryvyi Rih region's mining enterprises play a special role in the iron ore industry of the state.

About 60%-70% of the total iron ore reserves in Ukraine are located in Kryvyi Rih iron ore basin, and its iron ore enterprises used to supply and are supplying more than 85% of the national iron ore production volume [6].

Iron ore mining in Kryvyi Rih has been carried out for more than 140 years by both open-pit/surface (followed by beneficiation) and underground mining methods. In the last 7 years, after more than two decades of recession, there has been a certain tendency to increase the volume of iron ore output. Moreover, in some years, compared to the previous ones, iron ore production in Ukraine almost doubled [2-3].

Iron ore needs of Ukrainian enterprises and export supplies are provided by 9 national open-pit enterprises: the PJSC "Pivnichnyi GZK", the PJSC "Tsentralnyi GZK", the PJSC "Pivdennyi GZK", the PJSC "Inhuletskyi GZK", the PJSC "Poltavskyi GZK", the OAO "Yerystivskyi GZK", the GZK of the PJSC "ArcelorMittal Kryvyi Rih", the GZK Ukrmekhanobr, the PJSC "MMK im. Illicha" ("Ilyich Iron and Steel Works of Mariupol") as well as ten underground mining enterprises including the PJSC "Kryvyi Rih Iron Ore Works" (KZRK) (Oktiabrska, Ternivska, Rodina, Hvardiiska underground mines), the PJSC "Zaporizhzhya Iron Ore Plant (ZZRK)", the PJSC "Sukha Balka", the mine administration of "ArcelorMittal Kryvyi Rih" (Artem underground mine), the PJSC "Tsentralnyi GZK" (Ordzhonikidze underground mine). At national iron ore underground mining enterprises, the mining depth is approaching 1542m-2500 m, in GZK open-pits - 550 m with an outlook for 750m).

Along with increasing the level (depth) of mining, technical and economic indices of iron ore production are deteriorating (Table 1.1). This is primarily a consequence of lack of new mining technologies and highly efficient mining machines and mechanisms, which increases the time for preparing new underground mining levels and does not allow increasing efficiency of iron ore mining.

This is explained by a number of both natural and artificial factors. These factors are essential for further research in the direction analyzed.

Yet, qualitative indices of iron ore materials produced in our country (the percentage of iron content, harmful impurities, physical and mechanical properties of ore and country rocks) are inferior to those of some foreign mining enterprises. Therefore, extraction of crude ore and production of marketable iron ore products with appropriate quality indices require a lot of power and material expenditures, this entailing an increase of iron ore costs.

Table 1.1 – Forecast indices of Ukraine’s iron ore underground mining enterprises

Mining facility	Mining depth, m	Forecast yearly output, Mt	
		ore	quartzite
Yuvileina underground mine, Kryvyi Rih	2060-2200	1.5	5.0-7.0
Frunze underground mine, Kryvyi Rih	1500-2500		
Rodina underground mine, Kryvyi Rih	1765-1900	3.0	8.0-12.0
Oktiabrska underground mine, Kryvyi Rih	2015-2500		
Ternivska underground mine, Kryvyi Rih	1955-2200		

Hvardiiska underground mine, Kryvyi Rih	1990-400		
Artem-1 underground mine, Kryvyi Rih	1490-1700	0.7	3.0

At the same time, both geopolitical and political factors of recent decades have significantly affected priorities and the state of Ukrainian mining and metallurgical companies and, above all, iron ore prices (both internal and external) [3, 7].

In recent years, problems of mining enterprises have deteriorated. This is due to the fact that with Ukraine's gradual integration into the European market structures, the issue of ensuring implementation of effective technologies at national enterprises at all levels of iron ore production and processing is extremely acute.

Therefore, Ukrainian mining companies have to take a number of appropriate measures to get out of the strategically unfavorable economic situation. Unfortunately, these measures, which are not always justified, are far from being sufficient. According to the authors' non-categorical opinion, main reasons for this condition include:

– lack of the state's vertical economic management and coordination of enterprises' activity in the mining and metallurgical industry;

– the human factor of business owners;

– incomplete scientifically substantiated developments to determine effective directions for increasing energy efficiency of iron ore production and programmes of their practical implementation at iron ore mining enterprises;

– lack of the integrated approach to implementing measures aimed at reducing or, more precisely, inhibiting increase of iron ore production cost rates.

Iron ore underground mining is characterized by annual increase of production costs by almost 133.5% on average [2, 3]. The share of components of the entire cost structure [3] also changes, with electricity becoming the key factor here.

This is confirmed by the fact that, as already noted above, national mining enterprises are energy-intensive.

In such difficult conditions, it is necessary to enhance competitiveness of Ukraine's iron ore mining enterprises, which can be achieved by solving a double problem – to improve the quality of iron ore materials extracted and reduce the cost increase rate, thus reducing the cost of this type of products. This task is of national strategic importance.

1.2 Energy-efficiency of iron ore underground mining enterprises

Power engineering of mining enterprises and other power consumers is a component of the electric power complex – *power supply-consumption*. This fact imposes inseparability of connection between energy efficiency of both power supply and power consumption.

To assess the ability of a country to use and save energy resources, such a significant indicator as energy intensity of gross domestic product (GDP) is studied (Fig. 1.3). International experts say that in 2016, GDP energy intensity (thousands of o.e. 1000$) in the United States was 0.154; in Ukraine – 0.426, i.e. 2.8 times higher (in Vietnam – 0.215, Bangladesh – 0.126, Russia – 0.243) *. According to Ukraine's GDP energy intensity and despite the fact that in 2013 it decreased by 55.6% as compared with 1990, this figure remains one of the worst, at least in Europe.

Unfortunately, even in the forecast version (Fig. 1.3), in 2035 energy intensity of Ukraine's GDP is expected only at the level of 0.17.

Fig. 1.3 – Dynamics: the fact-forecast of energy intensity of Ukraine's GDP*

Unfortunately, at this stage, such a comparison with the industrialized countries of the world (and not only with them) is far from being in favor of Ukraine.

* Note: the Ministry of Economy of Ukraine provides lower indices.

* Note: in recent years, methods of evaluating Ukraine's GDP have been adjusted according to international standards considering purchasing power parity.

The source of danger to the energy sector of Ukraine is largely the state itself. Unfortunately, it is characterized, by underestimating importance of reforms aimed at increasing well-being of enterprise owners and ordinary Ukrainians, as well as by a hostile attitude to any attempts to destroy traditional inefficient forms of relations between power consumers and the energy sector itself.

In general, direct financial losses in power engineering cause cumulative losses in other industries, including the industrial sector of Ukraine as the "lost" money could be directed to development of the state economy [10].

Provision of Ukraine's energy security involves two directions. Implementation of the first direction provides:

– maximum use of available energy resources and sources due to intensification of national mining volumes, increasing treatment depth, new energy conversion technologies, use of secondary energy resources;

– avoidance of monopoly dependence on energy import through diversification of energy sources and transportation means;

– modernization of fixed assets primarily of fuel and energy complex enterprises (the level of fixed assets wear in fuel and energy complexes is about 60%);

– development of measures to ensure economic activity in case of unforeseen circumstances in the fuel and energy complex or with the supply of fuel and energy resources.

Implementation of the second direction should ensure:

– change in the structure of industrial production by reducing the specific weight of energy- and resource-intensive industries;

– integrated modernization of Ukraine’s economy on the basis of energy saving, introduction of the latest energy-saving technologies, up-to-date telecommunication and computer networks;

– reduction of inefficiency of the use of fuel and energy resources as well as secondary energy resources;

– expansion of the use of alternative energy sources; and

– formation of people’s energy-saving worldview.

Analysis of priorities of both directions of ensuring energy security indicates improved energy efficiency of all production facilities in Ukraine as a key area of the state's efforts.

In other words, at present, some conditions have objectively developed that contribute to searching for a fundamentally new approach to providing energy resources to all industries and the population. There is no alternative to improving energy efficiency of all activity areas. In industry, problems are caused by the use of outdated and inefficient equipment (especially in the mining and metallurgical industry).

It should be noted that issues of controlling power consumption have not always been ignored both in the country as a whole and in industries and enterprises in particular. Over the years, each enterprise has elaborated and is elaborating some steps to save energy resources, upgrade basic and auxiliary equipment, use new technological processes, etc. However, in the history of Ukraine as a state, the question of transition to energy-saving development has never been as acute as it is now. It is clear that this problem is not simple and its solution requires significant investments. Meanwhile, there are some far less expensive solutions to the problem.

Moreover, in this aspect, iron ore mining enterprises are unique, as approximately 90% of the total energy consumption for iron ore production is electricity, that is, electric power (Fig. 1.4).

Over the past 5-10 years, the share of electric power consumption in extraction of one ton of crude ore underground has increased [3].

It is important to note that with a decrease in iron ore production at absolutely all mining enterprises of Ukraine compared to 1990*, electricity consumption for the analyzed years almost remained the same – 350M kW*h. For example, since 2003 natural gas consumption by all Ukrainian iron ore mining enterprises has been constantly decreasing.

In this regard, the need for national mining enterprises to develop energy-efficient strategies, projects and programmes with an emphasis on improving the power sector to solve this global problem is growing.

Note*: In 2018, Ukrainian iron ore mining enterprises produced about 78% of crude iron ore as compared with 1990.

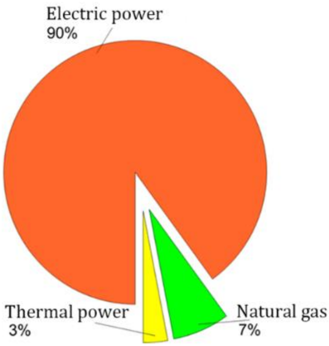


Fig. 1.4 – Power consumption components at Ukraine's iron ore nderground mining enterprises

At the same time, continuing the analysis of iron ore cost components, without deviating from the previously declared aim of the research, we note the fact that the cost level at all national underground mining enterprises is not directly connected with the power consumed [42].

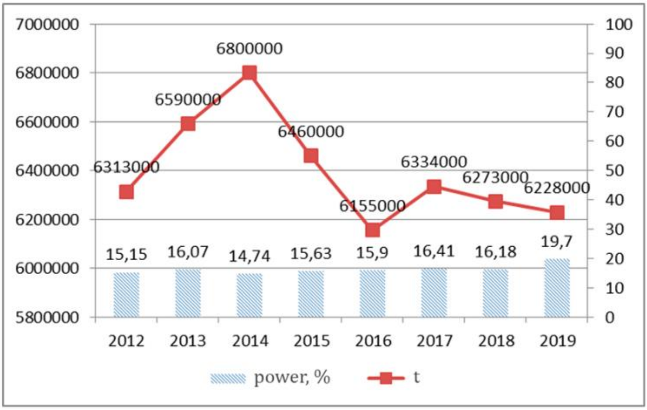
Moreover, the level of electricity as a component of the iron ore production cost is fluctuating in nature (Fig. 1.5) and does not directly correspond to output volumes.

According to the indices (Fig. 1.5), since 2017, certain positive changes have again turned into negative ones as for electric power efficiency of iron ore underground mining enterprises.

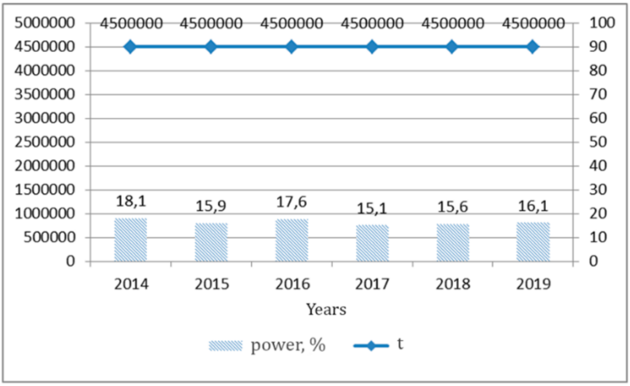
Energy efficiency of power consumers includes four aspects [42]:

– control of energy flows and their rational use;

– energy saving, with reduction of losses and energy-intensity of products, including that of the energy component in product cost;



a)



b)

Fig. 1.5 – Averaged indices of the power segment in the complex of iron ore materials cost and output volume at underground mines of Kryvyi Rih (a) and Zaporizhzhya (b) iron ore plants

– electrification (according to H.M. Kryzhanovskyi) as an increase in the range and quality of direct and indirect energy services; and

– environmental safety by preventing harmful emissions into the atmosphere from producers and consumers of various types of energy.

Energy flow control at enterprises consists in arranging a system of power accounting and rational use of available energy resources. Here we can talk not so much about saving the amount of fuel and energy resources, but about economic effects from implementation of the above measures.

In any case, control of energy flows at enterprises, including mining ones (Fig. 1.6) should be based on a developed programme to implement which a substantiated structure is required with enterprise managers, technological and power engineering services as its key factors.

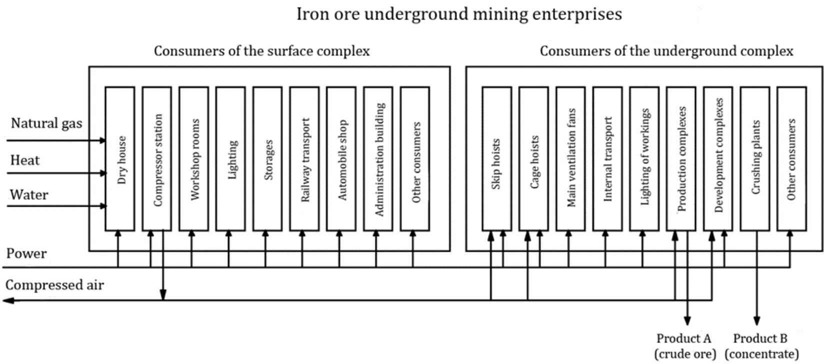
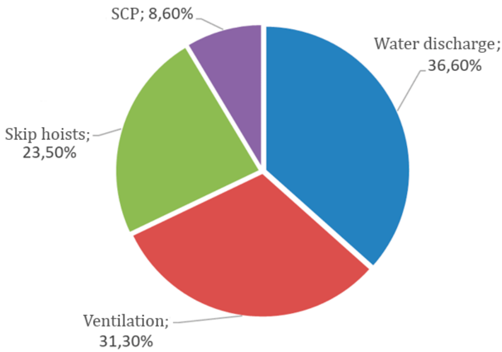


Fig. 1.6 – Power flows of iron ore underground mining enterprises

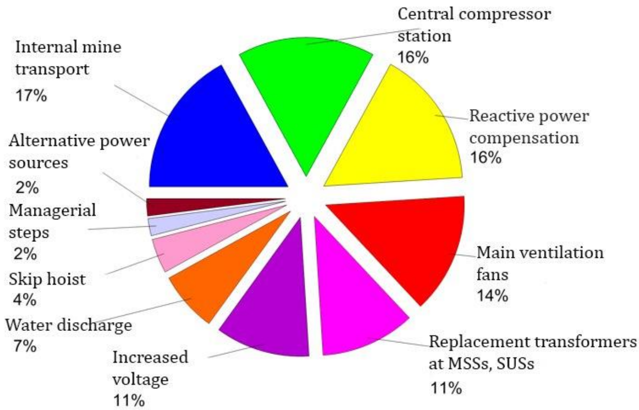
In the final version, to achieve the desired effect in this price-oriented sense, this "controlling" system of the enterprise should be based on or more precisely implemented by *the ACS of electric power consumption* with a subsystem of *the ACS of power flows* as an option. When developing the ACS, it is necessary to rely on a comprehensive solution to the problem including the need to significantly reduce losses in power delivery that occurs when conducting mining operations at a particular iron ore mining enterprise as well as the use of alternative and low potential energy resources, especially fuel and energy ones [9, 12-32].

Yet, all "good intentions" to improve energy efficiency of iron ore production will remain only formal, if in the end the problem of controlling the technology of this complex functioning within the framework of, first of all, the enterprise itself and especially such energy-intensive enterprises as mining and metallurgical ones is unsolved.

The potential to achieve this goal in tangible volumes at enterprises of this industry is shown in Fig. 1.7 [58].



a)

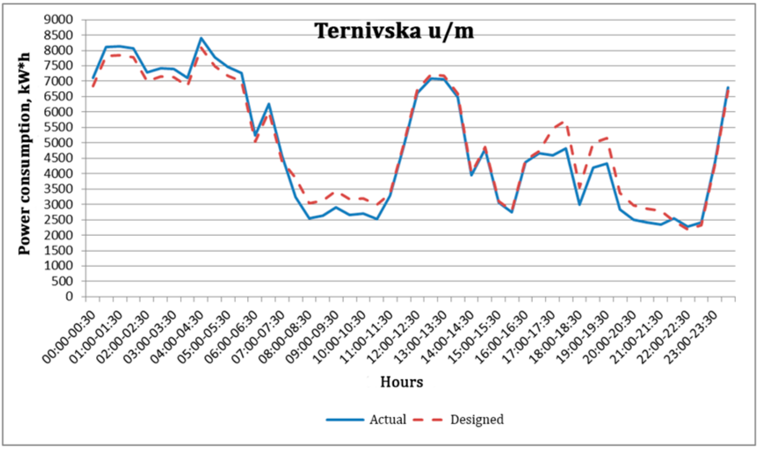


b)

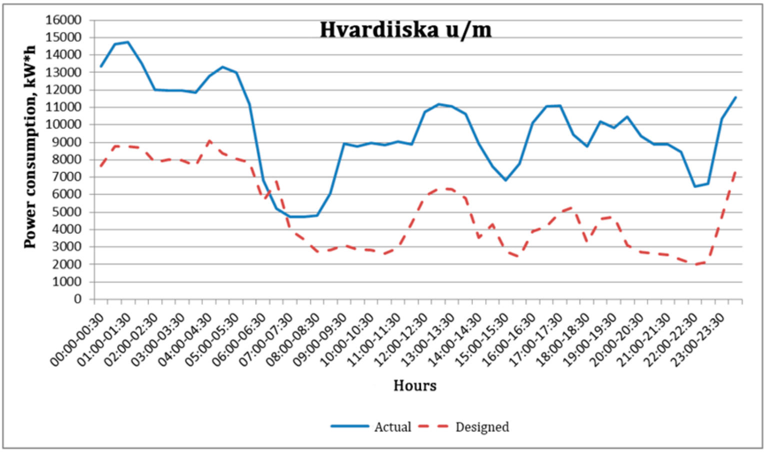
Fig. 1.7 – Current power consumption levels by types of consumers (a) and optimistic potential of reaching energy efficiency (b)

The basis for this is legislative documents on the issues analyzed. Moreover, concerning the problem of energy efficiency of iron ore underground mining enterprises, we would like to note that changes introduced by enterprises themselves gave a positive result in 2015 and 2017.

Fig. 1.8 reveals the results of implementing "manual control" over electric power flows on the time-of-day basis at some underground mines. As we can see, there are positive results as well as significant potential for further research.



a)



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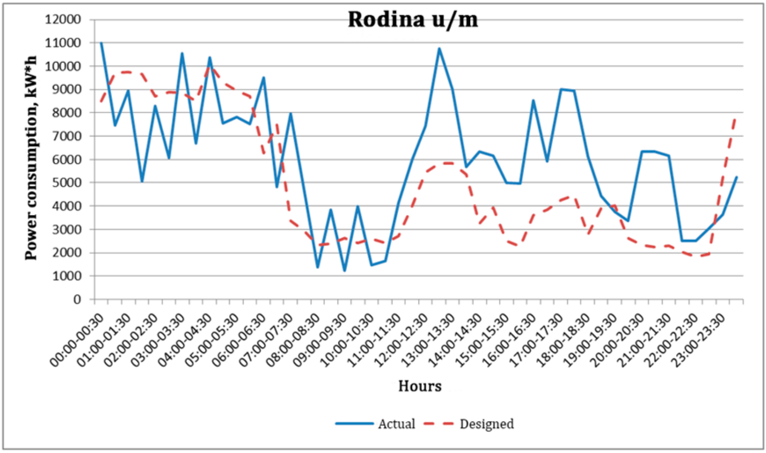
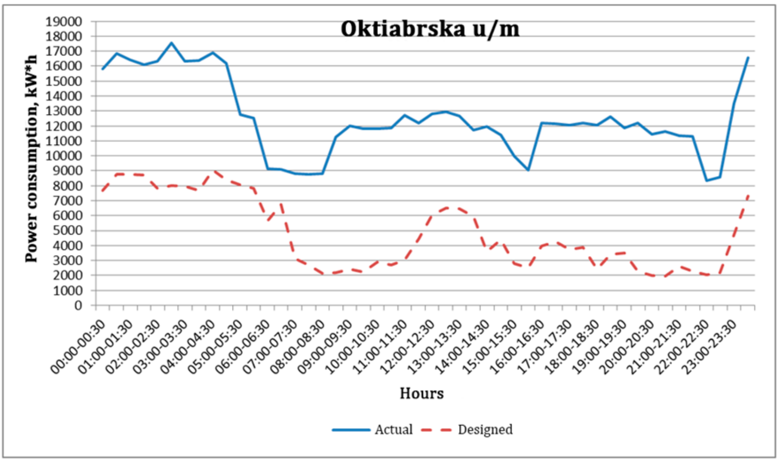


c)



d)

Fig. 1.8 – Designed and actual power consumption levels at underground mines of Kryvyi Rih iron ore basin with introduced 'manual control' over power flows: a) Ternivska u/m; b) Hvardiiska u/m; c) Rodina u/m; d) Oktiabrska u/m

The research formula implies that one of the really necessary and sufficiently effective ways to solve the problem of reducing, or, more precisely, actively curbing the increase rate of iron ore production costs is by developing and implementing a strategy at national iron ore mining enterprises, taking into account specific features of their energy-efficiency component and their economic development as the key factor of their competitiveness.

1.3 Substantiation of forming evaluation indices of energy efficiency in iron ore mining

There are some indices for evaluating energy and power efficiency of enterprises [107-109]. Without detailed analysis, we note that in order to evaluate energy efficiency in production and determine effectiveness of energy efficiency measures, objective indices reflecting the real use of energy resources and enabling comparison of evaluation results with maximum possible energy efficiency indices are required.

In any energy consumption there is a useful component and losses. Useful energy is understood as part of the energy spent, which is directly aimed at fulfilling the goal and meeting the needs of production.

The share of utility of energy consumed determines the value of the utility factor, which is the most general indicator of energy efficiency [110].

The value of the utility factor characterizes the power supply process as a whole, including its scientific and engineering level, management and culture of operation. The utility factor can be determined for a separate power consumption process, an individual enterprise or a city, and a region as a whole. In the latter case, the factor is the most important indicator of efficiency of the power supply system of both the state and an enterprise.

Unfortunately, in recent years, Ukraine has not conducted any specific multi-vector studies to determine the utility factor of energy resources on the state scale. Therefore, its value can only be evaluated approximately. Based on the data of previous years, foreign analogues and taking into account changes in the structure of power consumption, it is possible to determine the most likely approximate value of the utility factor of energy resources of Ukraine in 2000-2015 that makes about 42% [111].

In its turn, the utility factor is defined as the product of partial efficiency factors of various parts of the energy supply process, including extraction, transportation, storage, processing and conversion of primary (natural) energy resources, as well as transmission, distribution and use of converted energy carriers. Ratios of partial efficiency factors indicate energy efficiency of each link.

To determine other indices of energy efficiency, it is necessary to classify energy losses. They are known [111] to be divided into reverse and direct. The direct ones include losses that cannot be eliminated by current methods and technologies. Considering technically constrained efficiency achieved at this stage, certain levels of the energy process and the utility factor as a whole are determined.

The reverse losses include those that can be eliminated by expenditures for reconstruction. Their value indicates technically achievable potential of energy efficiency. The real scale of energy efficiency can be much lower than the potential one and determined by the level of economically justified investments.

The dependence of implementation of reverse losses on the performed ones is the most important economic characteristic of energy efficiency. Sometimes their lower margin can be taken close to zero. These are the so-called low-cost measures, most often managerial ones. It is this option to improve energy efficiency that is used en masse at Ukrainian enterprises. Besides, it provides a considerable effect [111]. Yet, this direction as a possible way to achieve the desired level of potential has already been exhausted. Some new reserves should be involved in this process. The upper economic level of expenditures in each case is individual and determined by energy cost in an alternative version. It should be said that the economic marginal level of energy efficiency costs can increase significantly if the price of substituting energy resources considers provision of their natural reserves.

Besides, when determining energy efficiency indices, it is necessary to take into account the economic component of changing the cost of losses at the links of the energy process, as well as their quality.

Both of these factors must be considered in economic optimization of energy efficiency and fund distribution within an enterprise.

Thus, it can be asserted that the energy efficiency factor is a scientifically substantiated absolute or relative value of consumed fuel and energy resources (taking into account their regulatory losses) to produce a unit of products (works, services) of any purpose.

The difference between energy consumption based on old and new technologies determines the technical potential of energy saving.

Technical potential determines maximum energy efficiency. Part of the technical potential that can be profitable is energy-economic potential.

There is also an energy efficiency potential which is determined by the degree of awareness of relevance of the energy saving task by all people implementing it.

To assess energy efficiency of production, it is necessary to determine the reasons for increased energy consumption.

The main reasons for increasing energy costs can be divided into three groups:

1. Managerial and operational: low culture of operation, insufficient technological discipline, lack of some control and metering devices, automation tools, low quality of repairs;

2. Raw materials-related: low quality of raw materials, basic and auxiliary materials and substances required for production;

3. Production-related and technological: extreme technical conditions of main and auxiliary technological equipment, poor introduction of new designs of equipment, technological processes and other achievements of technological advance aimed at improving energy efficiency of production.

As for electricity consumers (enterprises), here one of the criteria of energy efficiency which allows evaluating its dynamics and trends in the state and changes is an indicator of the energy-efficient production level (EEPL).

The EEPL allows evaluating the level of implementation of energy-efficient technologies, economic schemes, equipment, etc.

$$EEPL = D/W \tag{1.1}$$

where D is the result of the analyzed enterprise's economic activity, thou. UAH; W is total energy consumption for technological purposes, etc.

Without degrading efficiency of the above indices, we note that currently applied specific power consumption per t of iron ore production should be recognized the most realistic and at the same time sufficient indicator of energy efficiency of iron ore mining enterprises. This indicator is one of the designed indicators in enterprises' economic activity.

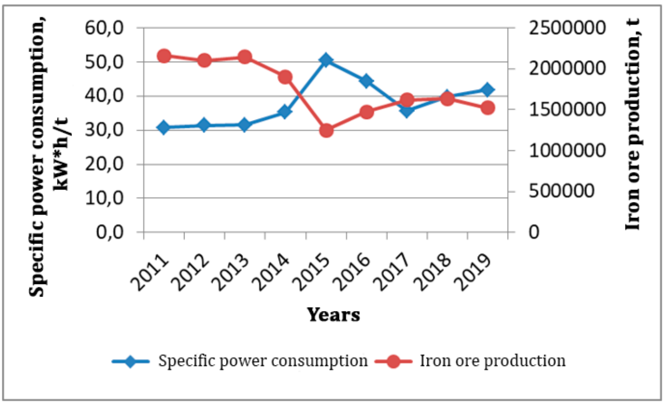
Some previous indices from the history of this process development look interesting in terms of energy efficiency of iron ore mining enterprises. So, in 1950-1988, in the USSR, electricity consumption for iron ore extraction and preparation for metallurgical production increased almost ten-fold, and in 2017 this indirect indicator reached 45.0 B kW*h.

In 2016, at national mining and beneficiation plants (GZK), electric power efficiency indices were as follows: average specific consumption of electricity at plants with pellets as final products was 62-63 kW*h/t, while at those with iron ore concentrate – 38-45 kW*h/t.

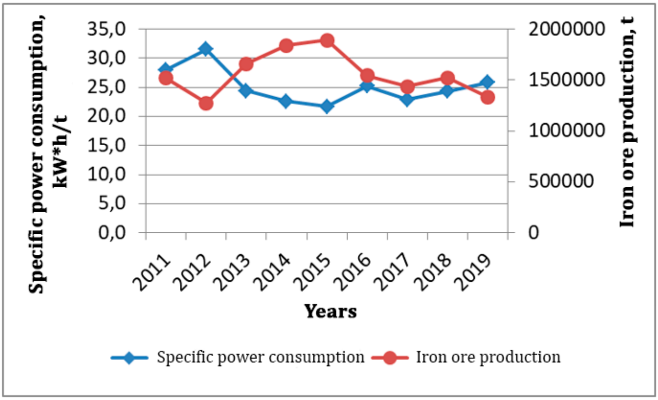
To compare the above indices with Russian GZKs, which are the closest in the technology of conversion stages, we note that in the last decade the level of their energy efficiency has steadily decreased, although at some GZKs of the Russian Federation this figure is consistently high. Thus, at Kostomukshsky GZK, specific costs for pellet production in 2017 reached 66.7 kW*h/t (the highest among Russian GZKs), at the same time for concentrate production, the figure was 39.5 kW*h/t (the lowest among GZKs of Russia).

In 2017, at underground iron ore mining enterprises of Ukraine, specific power consumption per 1 t of crude ore was 25-45 kW*h/t, i.e. the difference doubled. However, at national coal mining underground enterprises, this difference was about ten-fold [43-46, 55, 58].

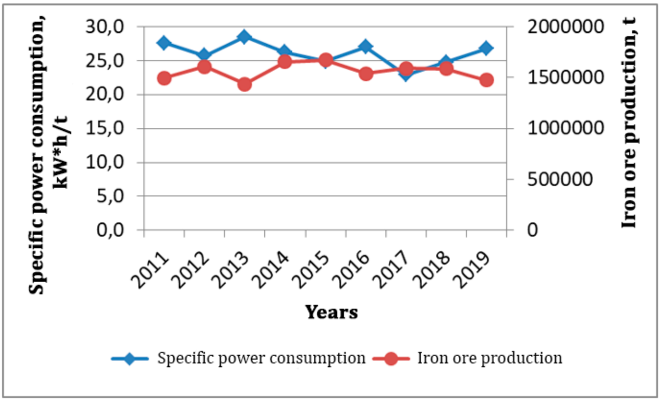
However, iron ore production, or rather the level of its volume fluctuations, is determined by the iron ore market and in this respect, we cannot affect the process of power consumption in any way. Therefore, it is logical that the authors are primarily interested in power engineering of the process and possibility of influencing it by tools of power engineering itself, this being characterized by significant fluctuations (Fig. 1.9).



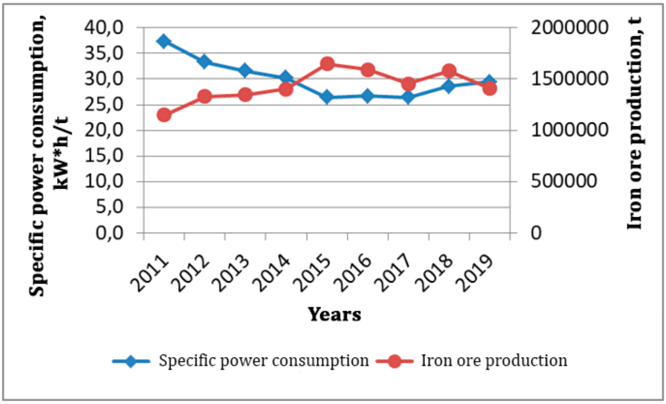
a)


Specific power consumption, kW*h/t
35,0
30,0
25,0
20,0
15,0
10,0
5,0
0,0
2000000
1500000
1000000
500000
0
Iron ore production, t
2011
2012
2013
2014
2015
2016
2017
2018
2019
Years
Specific power consumption
Iron ore production

b)


Specific power consumption, kW*h/t
30,0
25,0
20,0
15,0
10,0
5,0
0,0
2000000
1500000
1000000
500000
0
Iron ore production, t
2011
2012
2013
2014
2015
2016
2017
2018
2019
Years
Specific power consumption
Iron ore production

c)

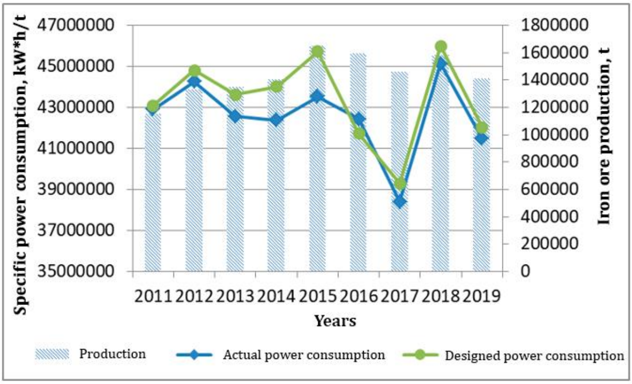


d)

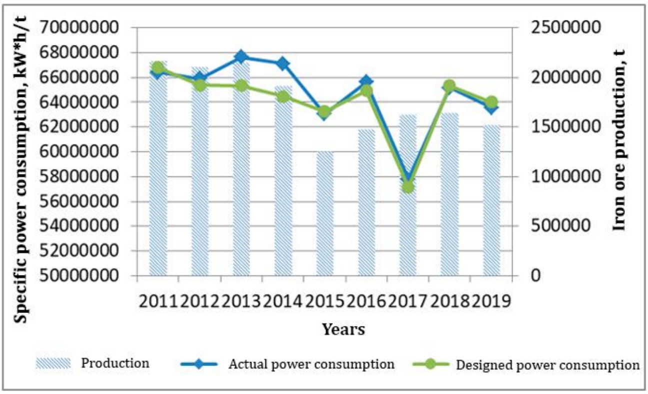
Fig. 1.9 – Fluctuations of iron ore production and specific power consumption of iron ore underground mining enterprises of Kryvyi Rih iron ore basin:
a) Rodina u/m; b) Ternivska u/m; c) Hvardiiska u/m; d) Oktiabrska u/m

At the same time, fluctuations in specific power consumption per 1 t of extracted iron ore are a priori unpredictable from the entire range of efficiency factors of iron ore production (Fig. 1.10). Besides, this factor was on average 2 times different for various iron ore underground mining enterprises in some years [43].

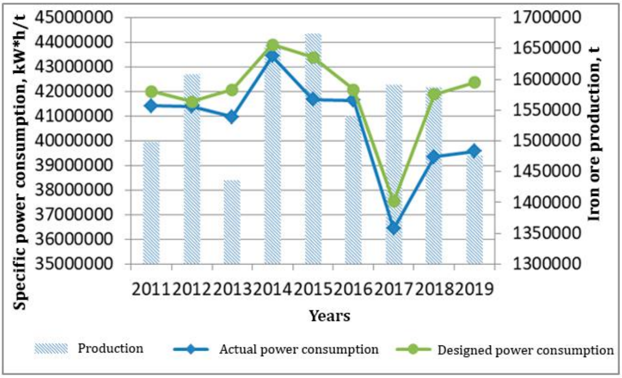
Without rejecting a number of objective reasons, we note with a significant level of confidence that the above is a direct consequence of the fact that mining enterprises usually inadequately predict the cost of raw materials extracted (rather based on the achieved results), including the power segment in this complex factor.


Specific power consumption, kW*h/t
47000000
45000000
43000000
41000000
39000000
37000000
35000000
1800000
1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
Iron ore production, t
2011 2012 2013 2014 2015 2016 2017 2018 2019
Years
Production
Actual power consumption
Designed power consumption

a)


Specific power consumption, kW*h/t
70000000
68000000
66000000
64000000
62000000
60000000
58000000
56000000
54000000
52000000
50000000
2500000
2000000
1500000
1000000
500000
0
Iron ore production, t
2011 2012 2013 2014 2015 2016 2017 2018 2019
Years
Production
Actual power consumption
Designed power consumption

b)



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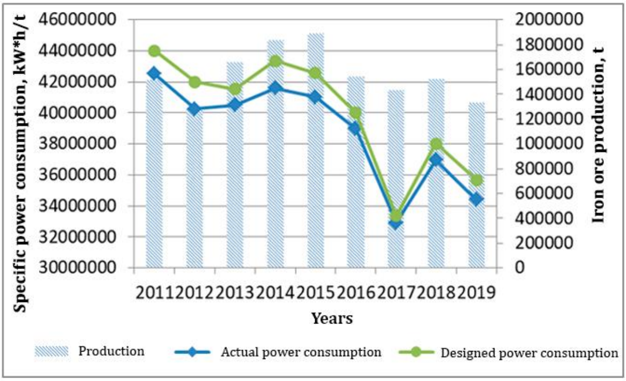


d)

Fig. 1.10 – Iron ore production and actual/designed power consumption of iron ore underground mining enterprises of Kryvyi Rih iron ore basin:
a) Oktiabrska u/m; b) Rodina u/m; c) Hvardiiska u/m; d) Ternivska u/m

As follows from Fig. 1.11, until 2019 (the year of transition to a new tariff network), at all mines analyzed at night, when the price of power is minimal, actual consumption exceeds the designed one by 12-15%, but during peak hours the actual consumption is lower than the designed one. This suggests that enterprises' potential to regulate power consumption by time-of-day tariffs are not used to the maximum and savings on electricity payment are not corrected according to actual operation of these types of enterprises.

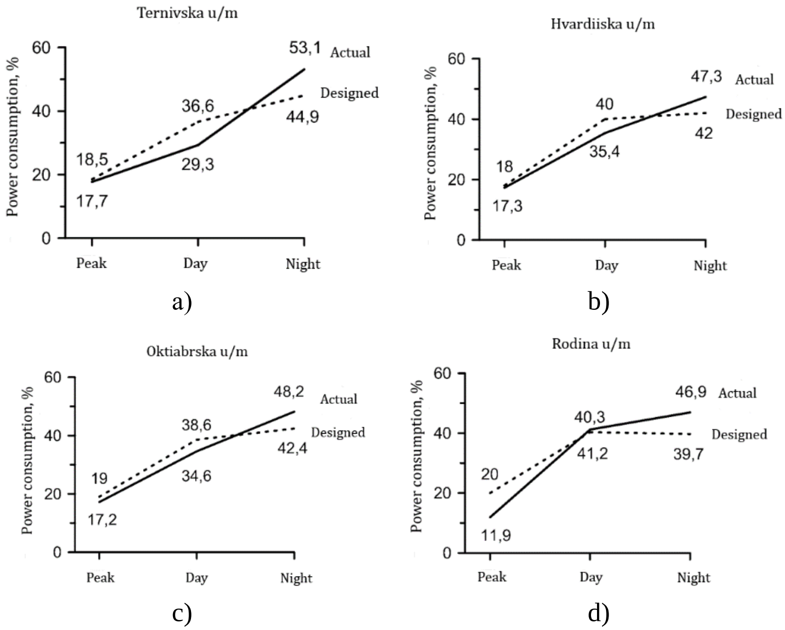


Fig. 1.11 – Averaged ratios of designed and actual daily indices of specific power consumption in 2014-2018 at underground mines of Kryvyi Rih iron ore basin: a) Ternivska u/m; b) Hvardiiska u/m; c) Oktiabrska u/m; d) Rodina u/m

Yet, from the indices analyzed for the "old" 3-rate electricity tariffs, as well as for the "new" ones starting from 2019 [41, 42, 87, 220] it can be concluded that the "designed" and "actual" figures differ. This once again emphasizes the need for more meticulous control of this process that can be achieved only by the relevant structure of *the ACS of electric power consumption*.

1.4 Legislative framework of Ukraine as a basis for solving the problem of increasing energy efficiency of iron ore mining enterprises

Ukraine's legislation for power engineering is one of the priorities and directions of implementation of the state energy strategy [133].

This is confirmed by the fact that from 1991 to 2019, more than 60 laws, resolutions and decrees concerning problems of increasing efficiency of production, distribution and consumption of electric power were adopted and introduced in Ukraine. A large number of legislative acts indicate significance of the problem analyzed as a national and strategically important issue for the security of Ukraine, its power independence from donor countries.

The role of legislation in implementation of the state energy saving policy is to identify social orientation and place of the energy law in determining functions, forms and content of the state's activities which are aimed at rational use and economical consumption of primary and converted energy and natural energy resources in the national economy and which are implemented by technical, economic and legal methods.

Functions of energy law concerning the energy saving policy are:

– the law framework of the legal support mechanism to conduct the policy in the field of energy saving;

– a means of achieving the goal and objectives of the energy saving policy;

– a legal form of policy implementation in the field of energy saving;

– a guarantee of the energy saving policy provision.

Forms of activity include:

– concepts of the energy saving policy;

– the energy saving policy programmes;

– normative and legal acts of the policy in the field of energy saving;

– laws of the energy saving policy;

– by-laws of the energy saving policy;

– sectoral normative and technical acts of the energy saving policy.

The mechanism of legal support of the energy saving policy is a set of legal norms that ensure regulation and implementation of internal and external activities of the state aimed at effective use of fuel and energy resources. The structure of legal support includes:

– legal regulation;

– managerial and functional support;

– legal liability.

Any economic, institutional and other transformations in energy saving, as well as the national and foreign policy in this area should be based solely on the provisions of Ukraine’s laws. It is the laws that should become the basis for legal regulation of energy relations. Such regulation should be as clear and detailed as possible to minimize adoption of by-laws and avoid discriminatory application of legislation.

At present, each of the branches of the fuel and energy complex is guided by its own separate law and by-laws adopted for its implementation.

Thus, in power engineering, the Law of Ukraine *On Electric-Power Engineering*, in nuclear power engineering – the Law of Ukraine *On Nuclear Power Use and Radiation Safety*, in coal mining – *the Code of Ukraine on Mineral Resources* and *the Mining Law*, in the oil and gas industry – the Law of Ukraine *On Oil and Gas*, etc. are basic laws for the branches. The general character in the wording of many provisions of these laws causes the need to adopt numerous by-laws by various authorities. Such an approach to legal regulation creates conditions for different application of laws resulting in failure to achieve or incompletely achieve their goals and objectives.

1. Taking into account principles of creating and improving legislation of the fuel and energy complex defined by the strategy, its further development should be carried out in the following areas:

– adoption of laws aimed at solving key problems of fuel and power engineering as a priority, namely:

– systematization and ordering of property relations in the fields of the fuel and energy complex;

– a detailed definition of the structure of public administration, a clear distinction between these functions, in particular, concerning formation of activity rules on energy markets, regulation of powers and areas of responsibility of central and regional authorities, local self-government bodies dealing with energy supply and energy saving;

– improvement of functioning of the wholesale electricity market and determination of principles of the natural gas market functioning, legislative attachment of the function of establishing operation rules of markets to a controlling body;

– creation of effective financial and tax incentives to modernize energy facilities and use of energy-saving technologies;

– improvement of competitive markets of liquefied gas, petroleum products and determination of authority of the state regulatory body in this area, prevention of unreasonable administrative regulation of prices on competitive markets;

– regulation of conditions and rules to provide state support, including subsidies for enterprises of the fuel and energy complex;

– strengthening of environmental obligations of energy industry entities to reduce pollution and ensure civil protection concerning technogenic safety of the fuel and energy complex and increase responsibility for their violations;

– determination of the legal basis to form relevant structures and their authorities for controlling state corporate rights.

2. Development of legislative regulation in energy saving should enhance fulfillment of Ukraine's international obligations under ratified international energy agreements, first of all, *the Energy Charter Treaty* and *the Kyoto Protocol* within *the UN Framework Convention on Climate Change*:

– legislative support for fulfilling Ukraine's obligations under the Energy Charter Treaty should include mechanisms for accessing Ukraine's energy markets, creation and development of open competitive energy markets, promotion and protection of energy investments, energy product trade, energy transit, resolution of international investment and environmental protection disputes.

– legislative support of Ukraine's obligations under *the Kyoto Protocol* should ensure mechanisms for trading quotas for greenhouse gas emissions, in particular through implementing joint projects.

3. Development of legislative regulation in energy saving through the mechanism of adjusting Ukraine's energy legislation to the legal system of the European Union should enhance fulfillment of European energy legislation requirements to meet *the Partnership and Cooperation Agreement between Ukraine and the EU*, *the Programme of Integration of Ukraine into the European Union* and *the National Programme for Adjustment of Ukrainian Legislation to the Legislation of the European Union*.

Legislative regulation of energy relations should enhance international cooperation and lead to concluding relevant bilateral and multilateral international agreements aimed at satisfying national interests.

To some extent, it is in this direction that a new law on Ukraine’s electric power engineering – *On the Electric Power Market* – has been formatted [37].

Summarizing the above, we emphasize that the main task of energy saving legislation, or rather increasing power efficiency, is to create favorable conditions for effective use of fuel and energy resources, avoiding direct interference in economic activities of business entities. To implement this task, a mutually coordinated effective and transparent system of legislation on energy saving is required. This system should contain legal norms that would provide for an adequate combination of state regulation tools and encouraging business entities and the population to use fuel and energy effectively.

Unfortunately, a number of modern aspects that should and will be able to legislatively contribute to improving electric power efficiency of industrial and, mining enterprises in particular, have not yet become components in any of the existing legislative acts. We hope that such progressive areas to promote energy efficiency of energy-intensive enterprises as changing present-day structures of power supply systems controlled by Oblenergos (Ukrainian regional power distribution companies) into structures with distributing generation from both Oblenergos and autonomous energy sources (mini-power plants) will be reflected in relevant legislative documents. Of course, the above example is not the only one in the list of other points awaiting for their "legalization". This is a significant and urgent task, since on January 01, 2017 the institution of DSTU (state standards) was abolished.

To continue the above, we emphasize that the same analysis of current energy saving programmes indicates that with their significance for Ukraine, their main provisions are based mainly on many obvious areas and do not always take into account specific patterns inherent in the process of power consumption and energy-saving for a particular industry, including specification of power consumption in iron ore mining.

In this direction, the concept of functioning of mining enterprises as basic components of Ukraine's industry within the energy (power) policy in new economic conditions provides or should provide for both development of a multi-vector strategy for improving energy efficiency, and regulatory, legal, financial and economic tactics for its implementation.

It is important for the mechanism of application of privileges for developing, producing and commissioning energy-efficient mining equipment, as well as imposing sanctions for irrational use of fuel and energy resources to be based on indices and norms established by standards and other regulatory and directive documents.

At the same time, it should be noted that the main region for national iron ore production is Kryvyi Rih iron ore_basin, so a number of regional energy-saving programmes are adopted in relation to this particular industrial region. Due to this, in future, many things in Kryvyi Rih iron ore basin will be determined by and depend on implementation of one of the fundamental regional programmes – *Underground Kryvbas* [43].

The programme, in particular, states that energy-saving, the significant potential of which is in Kryvbas is an alternative to large investments and increased production of strategic iron ore materials which are difficult to implement in modern conditions. In future, the energy-saving policy in the Kryvbas iron ore industry will be aimed at developing advanced energy saving technologies to increase productivity and reduce energy and material intensity of production. These measures are high-cost, yet, together with the expected main technical and economic indicators of implemented technological equipment they should give an expectedly high economic effect at lower specific power consumption per unit of production, which will ensure the solution of a two-unit strategic state task – increasing energy efficiency and simultaneously reducing energy-intensity of iron ore production.

1.5 Energy efficiency of mining enterprises as a complex of research in the past and present

As noted in the previous sections of this study, issues of energy efficiency of the mining and metallurgical industry have always been and are the core of scientific search for a number of generations of researchers from different countries, including Ukraine [47-130].

The works of such scientists as B.N. Avilov-Karnaukhov, V. I. Weitz, V.M. Vynoslavskyi, S.A. Volotkovskyi, S.I. Vypanasenko, I.V. Hofman, S.P. Denysiuk, V.I. Hordeiev, E.S. Huzov, A.F. Zharkin, L.S. Zhyvov, V.T. Zaika, V.F. Kalinichenko, Yu.H. Kachan, E.A. Kireieva, O.V. Kyrylenko, R.A. Kihel, H.I. Kornilov, V.N. Kostin, B.R. Kudrin, V.R. Kuznetsov, N.I. Kuvaiev, S.D. Leporskyi, Leibov, V.N. Liakhomskyi, S.R. Maimizh, B.I. Mokin, H.H. Pivniak, V.A. Popov, L.I. Poltava, A.V. Pachovnyk, Yu.T. Rozumnyi, V.P. Rozen, Yu.I. Tuhai, O.M. Sinchuk, I.S. Samoilovych, A.A. Freitaha, H.S. Khromusov, V.F. Shchitka, A.K. Shydlovskyi, F.P. Shkrabets, M.I. Shulin, V.I. Shchutskyi are devoted to creating scientific and methodological bases and studying aspects of technological processes in power supply and consumption complexes. Foreign scientists have also contributed much to studying this problem.

In [76], which is one of the first works on analysis, evaluation and calculation of power complex parameters, the researchers try to substantiate connection between power consumption and technological parameters of a mining enterprise. The forms of connection are presented as power characteristics of both individual mechanisms and the enterprise as a whole. Ideas about standardization of power consumption are provided. This complex of researches is of considerable practical importance, but in their final version a number of the most important questions are not sufficiently covered, including methods of building power characteristics and using them for forecasting as well as the ability to control levels of power consumption in changeable conditions of mineral production.

In [114] the authors continue research into the above problems. Methodology of standardization and analysis of power consumption levels are given, the formula for building power characteristics that connect power consumption with productivity and other important factors that form the energy efficiency concept is recommended.

[76, 135] allow further research to identify general patterns of power consumption and create a scientific basis for studying energy characteristics and analysis of power consumption at a number of enterprises, in particular in the mining industry.

Special attention is paid to power consumption of mechanisms in [21, 26, 28, 31, 35, 71, 77]. For the first time, they consider energy characteristics as dependences reflecting the impact of peculiarities of performance of mining equipment on modes and levels of power supply. These connections are defined not only between the known main electric power indices, but also between the levels of power consumption in the function of some technological parameters of enterprises' performance as random values.

Taking energy characteristics as multidimensional statistical ratios, the author of [70] proposes the method of standardizing and analyzing power consumption of underground mining enterprises through using mathematical statistics and the probability theory. In further studies, energy dependences for individual mechanisms, mines and groups of mines are established on the basis of research data. At the same time, it should be noted that in the above-mentioned works, the impact of some other factors on power consumption is not investigated, except for the enterprise's characteristics, discrepancy between values calculated according to the proposed formulas, and the actual consumption of power in some cases exceeds the error allowed in this kind of calculations.

Methods for determining energy characteristics and analysis of power consumption proposed in [74] find their application in preventive standardization of power consumption in various industries.

In the above scientific papers, issues of analyzing power supply systems, modes of power consumption and quality of power are considered in detail, the ratio of power consumption and technological parameters in the form of energy characteristics of both individual consumers (machines) and the enterprise as a whole are studied. There are presented authors' visions of ways to improve energy efficiency of mining enterprises which used to be topical for that period. Meanwhile, it is impossible to ignore the fact that results of research works carried out in the 1960-1970s cannot be applied to current performance conditions of mining enterprises. Over the past years, such significant changes have been observed in mining equipment and technology that they radically affect patterns of the power complex formation at these types of enterprises.

Unfortunately, this problem has not been solved yet. Besides, in today's vision of the complex of improving energy efficiency in mining, standardization of power consumption should be assessed from this indicator forecast viewpoint.

In [122], basic principles and patterns noted in the works by predecessors are used as a basis for scientific research.

Specification of energy characteristics for individual mechanisms is an essential scientific component of the aforementioned works, since, taking into account various modes of operation and other conditions, the dependence of power consumption on mineral production has its own specific character.

The need to develop and improve this direction is caused by a number of objective reasons generated by specific features of iron ore underground production. Uncertainty of dependence of mineral production on changes in mining and geological conditions of enterprises' functioning is significant. After all, it is known that performance indices of mining enterprises are formed by a large number of factors, the manifestation of which is random.

Besides, uncertainty is also associated with instability of underground enterprises' production potential due to limited life-of-mine as a result of depletion of reserves. Moreover, life of underground mining enterprises is usually uncertain, so planning of the period and potential volumes of power consumption is almost impossible, and variability of the production situation is caused by the "mobile" nature of production, this leading to the need to revise and predict their production capacity.

Therefore, the authors suggest forecasting methods by building regression models on the basis of information about the links between modeled indices and the factors influencing them developed only up to a certain point in time that cannot give the desired level of probability of the results obtained. Moreover, these methods do not consider the impact of structural changes among production factors and do not reflect changes in functioning of power engineering after replacing technological complexes with other types and structures.

In turn, the forecast based on the exponential smoothing method considers the latest trends in changing economic indices, as the last values of the pre-forecast period are assigned with the greatest weight [113, 116]. Due to this, it is possible not only to increase accuracy of the forecast, but also reduce the amount of input information analyzed by excluding the "oldest" observations of temporary rows. Analysis shows that the exponential smoothing method provides good results in the forecast range of 5-10 years, if the observed process develops smoothly, without sharp jumps [118]

Mathematical models obtained by multifactorial correlation analysis can be used primarily in short-term planning [32-35]. It is possible to use them for a long term period, if the expected change in basic production indices affecting power consumption is known. To forecast power consumption, the expert method is also proposed. Now this method is preferable only with initial data processing due to large calculation errors [116].

A mining enterprise is a dynamic system that develops in time and space, the state of which is determined by a set of different mining, geological and technological factors that characterize production conditions. Some of these factors gradually change as mining develops (for example, the power consumed by fan installations), others depend on the time of year (for example, the water flow of relatively shallow mines) and the like. An objective assessment of the enterprise results from analysis of changes in its technical and economic indices and the factors influencing them.

When distinguishing basic factors affecting the levels and the entire process of power consumption, [9] suggests dividing them into controlled, partially controlled and those caused by random factors. At the same time, factors that to this or that extent have an impact on the state of a mining facility are divided into five groups: climatic, mining-geological, technological, managerial-economic and technical. The related factors determined by the expert method that influence power consumption of a mining facility are taken as a basis to form its mathematical model.

By analyzing the ways and results of researches [9, 25-29, 32, 48, 49, 60, 64, 75] to assess and develop methods and steps to improve energy efficiency of mining enterprises, we come to a rather unpleasant conclusion – the unconditional fundamentality of these studies is based on tactics, which or rather its model of power consumption of a mining enterprise is better. Of course, the model is the basis for developing methods for assessing power consumption. Yet, for the final search result, this is only an intermediate result, while the final result is a model to control the power-consumption process.

However, this goal should and can be achieved, in the best case, by developing a model for achieving energy efficiency of the complex *power* *supply-power consumption*, where both methodology for assessing and controlling the process and managerial measures, directions of minimizing power losses and optimizing electrical parameters of the entire power complex of the enterprise should be settled.

This multifactor task of achieving maximum efficiency should be solved through including both the enterprise as a whole and local power receivers of this complex into the structure of management.

To assess the level of competitiveness of iron ore production on the mineral market, there is a need to plan power consumption not only for the long term (a year, a quarter, a month), but also for a day or for another short-term period, depending on the order for the volume of minerals, which should be both mined and sold. For these conditions, none of the methods discussed above has the prospect of application, since such a need is not taken into account.

The general remark regarding the results of the works presented above is that they do not sufficiently cover changes in mining factors as for their operation and regularities inherent in power consumption of both underground mines in general and individual technological areas of iron ore production. From retrospective viewpoint insufficient attention is paid to patterns that characterize changes in the parameters of underground power grids and their consumers during their operation.

At the same time, these works are of great theoretical and practical importance and have become a foundation for forming the structure of the current research.

Analysis of available scientific publications of the last decade shows a significant number of studies of a sufficient scientific and practical level on the problem in question belonging to foreign scientists [91-106].

Thus, in one of the latest researches [32], a modern methodology for studying the levels of power consumption at coal mines based on Markov models is proposed. When describing these methods, we should admit that it is impossible to take into account all the factors of power consumption to be determined by a particular mathematical apparatus, since almost each of the components of the power consumption technology rarely remains constant even for a short time, and individual factors affect each other. It is reasonable that since there is no strict functional dependence between the levels of power consumption and determining factors of this process, it is possible to specify patterns of its formation by using the mathematical apparatus of the probability theory and mathematical statistics.

Mathematical and, first of all, correlation-regression methods allow not only determining patterns necessary for research, but also providing their quantitative evaluation. Correlation analysis makes it possible to determine how power consumption changes on average depending on changing factors and how close the relationship between the function and factors is.

[91] outlines theoretical principles and methods of operational forecasting of active and reactive loads of industrial enterprises in this very direction. There are price models for developing structures of *the ACS of electric power consumption*. Simultaneously, applying possibilities of using the results of the above studies to certain mining enterprises, we note that being substantiated and relevant they are more theoretically oriented.

[96-100] highlight a purely economic problem of controlling electricity costs of industrial enterprises. Elements of such a "purely economic" approach to solving the problem of power flow control are quite interesting and should be able to find their application as a research segment when building the ACS of electric power consumption.

Scientific researches set forth in [101] are aimed at dealing with tools to form the power control system as the basis for controlling energy efficiency of industrial enterprises in general, without taking into account specific conditions of their functioning.

In [102], the emphasis of research is on the important energy direction of industrial enterprises’ functioning – the conceptual basis to form the fuel and energy balance of a particular metallurgical enterprise. However, these studies are aimed at solving some other problems.

An interesting approach to solving the energy efficiency problem of various types of industrial enterprises, including mining ones, is set out in [103-106]. Yet, the basic component of presenting the results of these studies enables us to conclude about the somewhat practical emphasis of these searches suitable for a particular enterprise without any generalizations and options to extrapolate the research results to other types of enterprises.

[60] states that in conditions of electricity price increase and introduction of time-changing electricity tariffs, the analyzed enterprises – mini-steel plants can change their activities to reduce their electricity bills. The load model presented in the work is combined with formulation of the optimization method, which uses integer programming to minimize total power costs and satisfy the limitations of the production process. The case study of a steel plant shows that with optimal loads, a significant decrease in power consumption is possible during the peak period (about 50%) with the reduced cost of electricity (about 5.7%).

[47] presents an optimal model for controlling power consumption and its application to a South African coal underground mine. It shows how the optimal control model can be applied to improving energy efficiency. The electricity tariff is used as input data for the target function to obtain a solution that minimizes electricity costs.

[48] provides optimal integration based on modernization of previously known methods of power consumption control for a petrochemical plant taking into account uncertainty of power supply.

[49] presents an original integrated model of a coal open pit to support energy-efficient solutions. There is combined integral linear programming applied to formulating a common integrated model of operational power consumption of four general subsystems of open-pit coal mining – soil extraction and transportation, storages, processing plants and belt conveyors. Underground mines are represented as interrelated samples of four subsystems in the form of a sequence of operations, which are then adjusted to the data provided by mine operators. The solution of the integrated model provides synchronization of the subsystems to control power consumption and improve energy efficiency of the enterprise as a whole.

[50, 51] present assessment of energy efficiency for electric power machines of energy-intensive consumers aimed to quickly identify numerous technological problems associated with a production cycle. Development of smart data analysis methods has provided new opportunities to automatically process and analyze large amounts of collected data on power consumption levels. Yet, the data available from operating control systems is not usually relevant to perform such analysis and requires complex preparation – cleaning, integration, selection and transformation. The article proposes a methodology for analyzing power consumption data based on the "knowledge detection" application. Input data include observations of the production system’s behavior and relevant data on power consumption.

[53] states that gold underground mines with significant levels of underground operations require cooling and water reticulation systems for miners’ comfortable work at extreme depths. It is shown that these systems consume 40% of power supplied to mines of this mineral mining depth. Therefore, increasing energy efficiency in these systems will reduce electricity costs and operation expenditures of the mine as a whole. It is noted that for a particular mine, unique integration work is required to significantly increase energy efficiency. The strategy of the scientific approach outlined in the article reveals successful implementation and integration of cooling and water reticulation systems into the practice of a particular mine.

[52] notes that projects implemented in gold mines are aimed at reducing power consumption of large consumers, such as cooling, pumps, ventilation and compressed air systems. Therefore, this work discusses and analyzes different types of projects identified. The system specifies five projects and calculates potential savings for three of these projects. The total potential savings make 10.66MW. Therefore, it has been proven that some energy-saving projects can be identified automatically by using these parameters as part of *EnMS*.

[54, 55] investigate into issues of increasing energy efficiency of underground mines by improving performance of their ventilation systems. It is shown that power associated with ventilation of underground operations is a significant part of the mine's basic need for power and constitutes a large percentage of total operating costs. Ventilation systems can make from 25% to 40% of the total power cost and 40%-50% of mines' total power consumption. The total capacity of fans installed can easily exceed 10.000kW. The article shows how engineering design principles can be applied to increasing productivity and efficiency of mine ventilation, this leading to a significant reduction in power consumption, operating costs and greenhouse gas emissions.

Various approaches to finding ways to solve the problem are also outlined in a number of other works by foreign colleagues [47-67]. However, in one way or another, they duplicate research structures outlined above without any plagiarism though.

Analysis of the above-mentioned studies enables us to state that a great majority of well-known scientific searches are aimed at solving the analyzed problem for industrial (usually metallurgical) and coal enterprises.

Further scientific research allows the authors to confirm and supplement a significant difference in the functioning technology of underground iron ore enterprises' power engineering. At the same time, this "difference", according to the research aim makes the basis for holistic outlining of the problem and ways to solve it with the emphasis on finding solutions for iron ore mining enterprises with the unconditional use of chronology of existing positive research experience applicable to other types of enterprises.

Besides, paying a tribute to the aforementioned authors of different periods for the level of their scientific research, nevertheless, from the point of view of the research aim, we would like to note the following.

Summing up the results of the review of well-known scientific studies in the direction under analysis and assessing possibilities of applying their results in the present, we note that in all variants of the approach developed by the authors, in one way or another, the required level of searches has been achieved.

However, accessibility of this level is not enough for the final solution to the problem of increasing energy efficiency of iron ore production at modern underground mining enterprises, in particular by using effective methods of controlling power flows and distributing them among power controllers. This direction in its final version can be achieved by using *the ACS of electric power consumption* if the functioning algorithm for the entire managerial complex with elements of a potential smart version of current decision making is developed.

1.6 Preventive evaluation and main directions of energy efficiency improvement at iron ore underground mining enterprises

As mentioned above, mining enterprises are energy intensive. Thus, designed capacity of power receivers of national mining and beneficiation plants reaches on average 600 kVA, and that of underground mines – about 60kVA.

By the end of the 1980s, capacity utilization of basic technological units in the iron ore and coal industries of Ukraine had made about 90%-98%. The traditional and sufficiently effective direction to increase energy efficiency was consolidation of technological units and increase of single capacities of equipment. In general, that restrained, or rather did not contribute to the increase in specific power consumption per unit (ton) of minerals mined, as it reduced the weight of the segment of unproductive costs in the total amount of power consumption. A similar approach to reducing power losses was used for other enterprises – the larger the enterprise and the larger the output were, the lower power consumption per unit became.

The decrease in mining production and irregular capacity utilization of these types of enterprises in modern economic conditions have changed operation modes of technological equipment and, accordingly, power consumption, and consequently worsened energy efficiency affecting mining costs. This requires further analysis and development of appropriate measures.

The authors' research allowed formalizing impact factors of power consumption at iron ore underground mining enterprises (Fig. 1.12).

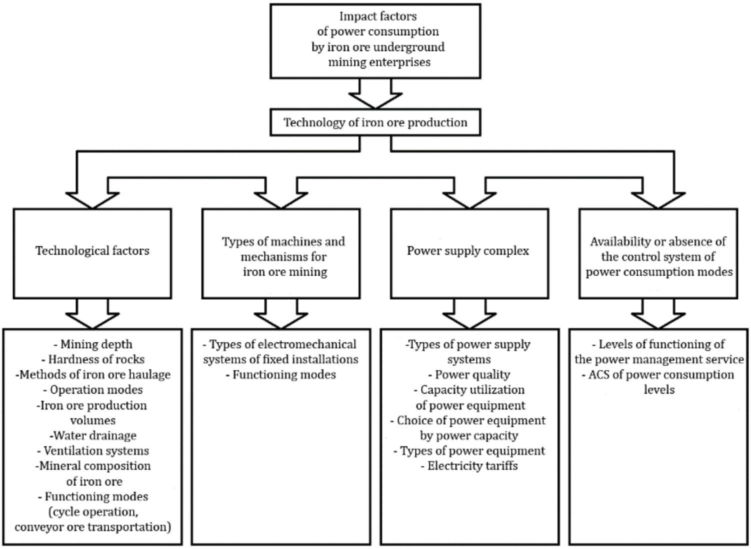


Fig. 1.12 – Structural reflection of basic impact factors of power consumption by iron ore underground mining enterprises

Energy efficiency of iron ore mining enterprises in modern conditions can be implemented by means of the sustainable mining technology in several directions (Fig. 1.13).

In this case, these directions can be implemented both autonomously and in combination, the latter having a more achievable effect. Let us conduct a cursory review of these directions.

First of all, this is reduction of losses both in power supply systems in general and in its individual components. Despite the fact that this problem in Ukraine has been paid constant attention to for a long time, unfortunately there is still no clear picture of its implementation in conditions when there are fluctuations in production volumes.

This fully refers to mining companies.

Besides, this aspect of increasing energy efficiency for operating iron ore mining enterprises has its own shade of complexity, as power supply in this case is complicated and it is almost impossible to radically reconstruct it. Basic trends in this aspect can involve optimization of established capacities of MSDS (main step-down substation) transformers by replacing them with the required power level (usually lower), as currently the transformers are loaded for no more than 20% [12-23]. This can be achieved by changing operating structures of power supply systems, for example by replacing the power supply circuits of MSDSs and withdrawing underloaded transformers into the "cold" or "hot" reserve modes.

Yet, analyzing this direction, it is necessary to note that the above-mentioned are only ancillary measures at the present stage of modernization of power supply systems.

The main modern tactical solution should imply restructuring power supply systems of iron ore mining enterprises in order to change them from structures with centralized power supply from Oblenergos into those with combined power supply – both from Oblenergos and from autonomous mini-power plants operating on renewable energy sources (water, air), which are available in iron ore mining. In other words, it is necessary to build power supply structures with sources of distributing generation [134].

Yet, an increase in unit capacity of iron ore mines' consumers and constant growth of underground power line lengths makes the issue of bringing distribution of 6-10kV closer to underground consumers and transition to power supply of mining machines and mechanisms to 660V instead of 380V.Problems of choosing a rational (in terms of efficiency) voltage that minimizes power losses in the grids of iron ore underground mines are directly related to the need of providing safety conditions [40]. For this reason, they cannot be resolved by considering economic factors alone. At the same time, a significant reduction in power losses can be achieved through applying advanced methods to calculating power grids and their load levels.

It is known that increasing productivity of some mining machines and mechanisms almost always leads to a decrease in specific power consumption. However, in the practical calculations of power supply systems, this principle is not reflected, and the effect of mining and engineering factors is not taken into account.

Application of energy-intensive consumers as power controllers is essential, though this aspect has not been widely used yet. This is done through introducing modern energy-efficient smooth/soft start and speed control systems of electric motors in machines and mechanisms.

This direction includes replacing obsolete energy-intensive types of machines and mechanisms with new ones equipped with modern types of energy-efficient electric drives.

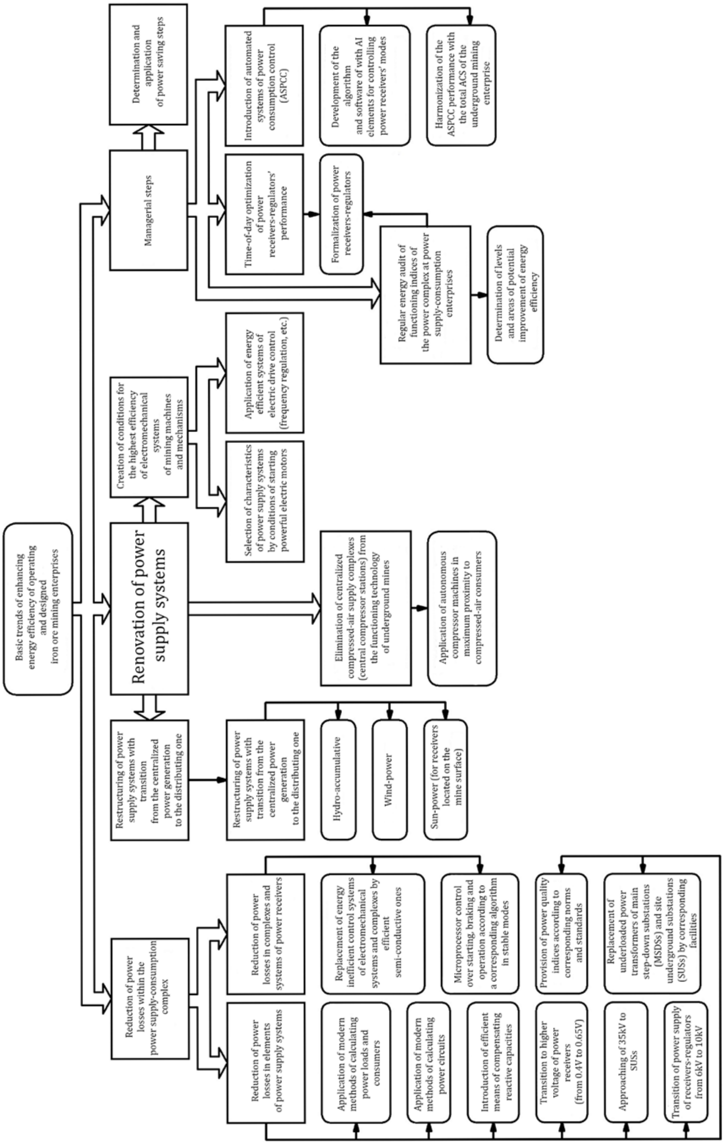


Fig. 1.13 Road-map of improving energy efficiency of iron ore underground mining enterprises

Another range of tasks also related to power losses involves choice of effective modes of reactive power compensation. It should be emphasized that in recent years, insufficient attention has been paid to this important issue. Possible changeable nature of mine power consumption requires an adequate approach in addressing reactive power compensation issues.

Energy efficiency problems are directly related to rationalization of power consumption modes. Adjusting load schedules can to some extent reduce the declared (paid) capacity during peak hours in the power system, thereby reducing the enterprise's electricity bills. A similar effect can be obtained by choosing characteristics of the power supply system according to the most economical and reliable criteria. These issues have also not yet been sufficiently resolved.

Changes occurring in the mining industry in terms of concentration of mining operations and their abrupt intensification impose a number of new challenges in forming power engineering problems and finding ways to solve them, which, unfortunately, have not yet been put into practice.

Recent practice has revealed a significant contribution to improving energy efficiency of iron ore mining enterprises as well as forecasting (planning) use of power resources resulted from power consumption monitoring (energy audit). Yet, unfortunately, in relation to iron ore underground mines, there are no scientifically sound guidelines on the scope, depth and frequency of energy audits.

The above issues form trends of solving the problem of improving energy efficiency of iron ore mining. At the same time, in case of iron ore underground mines, this problem results in another one – establishment and achievement of a really possible level of efficiency under given operating conditions.

Major research into power consumption at iron ore mining enterprises was performed in the 1960s-1970s, i.e. more than half a century ago. Therefore, application of the research results obtained in those years to mining conditions of ore underground mines, which have changed significantly, can cause and causes significant forecast errors negatively affecting both the industry and the country as a whole. In addition, in market conditions there is a need for short-term planning of power consumption. These requirements do not meet the previously developed methods of calculation. Over the past years, a number of changes have occurred in equipment and production technology designed for iron ore mining, this adversely affecting patterns of forming power consumption levels.

The reasons for this situation can be formulated as follows:

– lack of proper attention to this problem by mining enterprises' owners;

– lack of an effective and proven energy management system, in which the vertical control branch should include everybody from a CEO to a cleaner;

– lack of a realistic reasonable plan to increase energy efficiency and reduce power consumption per unit produced;

However, all the above arguments are the result of two major problems:

– the human factor;

– lack of scientifically substantiated assessments of the real state of energy efficiency at each specific enterprise, at each site of mining operations and differentiation of potential opportunities to increase this efficiency.

In the context of the above factors, we emphasize that it is not only and not so much as responsibility of the power supply service to implement measures to improve energy efficiency and hence competitiveness of mining companies. The desired effect will not be achieved without participation of enterprises' managers (owners) demonstrating their readiness to implement scientifically substantiated decisions aimed at improving energy efficiency in the structure of these types of enterprises.

SECTION 2
IMPLEMENTATION OF METHODS OF CONTROLLING POWER CONSUMPTION DURING DEVELOPMENT AND FUNCTIONING OF THE ACS OF ELECTRIC POWER CONSUMPTION AT IRON ORE UNDERGROUND MINES

2.1 Preconditions and technologies for building the structure of the automated control system of power consumption for iron ore underground mining

As noted in Section 1 of this research, considering importance and constant growth of the role of power in formation of costs for iron ore materials, mining enterprises try to reduce economic pressure on for this main indicator of enterprises' productivity. Unfortunately, these attempts are rarely based on the results of studies, and in their essence, as a rule, are reduced to "manual" redistribution of power flows by underground mining enterprises in hourly intervals.

Actual levels of power consumption by underground mining enterprises and those designed by the enterprises themselves have a significant difference, this indicating insufficient efficiency of this option of "manual" control [13-19, 146].

This discrepancy between deigned levels and actual indices does not contribute to achieving the expected level of energy efficiency of mining production. In this case, for the analyzed types of enterprises the problem of developing *the ACS of electric power consumption* becomes even more actual. For this reason, efficiency of the ACS will depend on the algorithm of its functioning – what parameters we choose and how, what processes and how adaptively it will automatically respond.

According to the researches presented in the previous section of this study, when forming regulatory criteria for *the ACS of electric power consumption* of iron ore underground mining enterprises, it is necessary to take into account specific features and technological capacities of power distribution between energy-intensive consumers, i.e. receivers-regulators. There is a rationale to that. Power consumption levels by energy-intensive receivers of iron ore mines differ: in some cases, drainage dominates, in others – ventilation or skip hoists [38]. Besides, such redistribution tends to constantly change its impact levels.

In other words, the functioning technology of *the ACS of electric power consumption* should be based on corresponding regulatory functions [38, 41, 42].

Main tasks of building the ACS include, on the one hand, integrity of its operation by optimizing power consumption levels (electricity consumption, corresponding costs) at iron ore underground mines using the appropriate time-of-day tariffs, and, on the other hand, the potential to increase the number of impact factors to expand the control system functions. We can add that according to conclusions 1-4, the analyzed process, as an integral part of the mining technology and a control object, is complex, multi-parameter, nonlinear and multi-connected [138, 139]. In this interpretation, tactics of the approach to creating an algorithm for of the ACS' functioning should be based on the theory of systems analysis. In this case, it is first necessary to determine the phase space, purpose and tasks of the control process [136, 140].

To simplify perception of the essence of the tactics of developing the algorithm of ACS operation, in the first approximation we will conditionally limit the range of hourly daily tariffs to two zones – "peak – off-peak". As will be proved later, it will not cause significant deviations to the final result (Fig. 5.1).

In a generalized form, the proposed tactics for building a general control algorithm is as follows. The algorithm of *the ACS of electric power consumption* is formed as part of nine blocks which, in turn, are connected with algorithms (2.3), (2.4) presented hereinafter.

As shown in [13], all these factors are quite informative for the current state of the system (underground mine). At the same time, depending on an individual mine, these parameters of ore flows, drainage, ventilation and air supply can affect the resulting factor (power consumption) in different ways. Thus, all these indices should be included in the state vector of our system $X = \{\ldots\}$. At the same time, depending on the degree of correlation between them, some of the parameters can be considered as control actions (the corresponding vector $U = \{\ldots\}$) or as disturbing factors (the vector $V = \{\ldots\}$). As a result, the generalized structural scheme of automated control of power consumption of a typical iron ore underground mine can look like (Fig. 2.1):

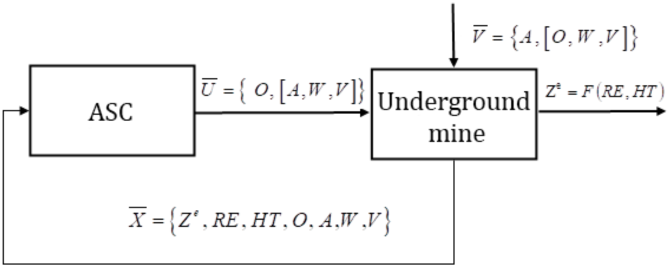


Fig. 2.1 Generalized structural diagram of automated control of power consumption in iron ore underground mining, where $\overline{X} = \{Z^e, RE, HT, O, A, W, V\}$ is the state vector with corresponding elements; $\overline{U} = \{ O, [A, W, V]\}$ is the control vector (of control actions); [13, 137] are optional elements of the vector; $\overline{V} = \{A, [O, W, V]\}$ is the vector of disturbing actions, where *O* is parameters of ore flows; *A* is air parameters; *W* is drainage parameters; *V* is ventilation parameters

According to the generally accepted classification [13], such a control diagram is closed-loop. The control object is the process of power consumption with the required frequency (day, month, year, etc.). The control subject is the ACS, the functional structure and algorithms of which will be developed and proposed later.

As mentioned above, the composition of elements of control vectors $\overline{U}$ and disturbing impacts $\overline{V}$ may differ depending on an individual underground mine. The final decision in this regard should be made on the basis of correlation analysis [146], which will be considered when developing control algorithms. In turn, the parameters Z^e, *RE*, *HT* are integral information components of the state vector of the system $\overline{X}$. The same applies to selection of control criteria in the minimax type or a marginal approach based on adoption of the main criterion, considering constraints.

Thus, the task is to develop algorithms, principles of operation and functional implementation of a system such as in Fig. 2.1 for two-, three- and multi-tariff control as well as checking its efficiency by computer simulation.

2.2 Development of the control algorithm based on fuzzy logic

Taking into account the above preconditions of nonlinear characteristics, incomplete data, multi-channeling in real production situations, modern smart approaches to introducing automated control based on fuzzy logic are promising [141, 142].

This approach provides an algorithm for a fuzzy control system (Fig. 2.2) to execute several controlling strategies (i.e. multi-channeling), namely:

$$S = \{O, O+V, O+W, V, 0, W+V, W, O+V+W\} \tag{2.1}$$

Each strategy determines the number of possible control actions (control channels) that need to be further implemented in the ACS. For example, according to certain sets (2.1), the number of parameters can be 0 (no control or "manual mode"), 1, 2 or 3. However, it should be noted that using this method, the number of channels can be further increased if necessary.

It should also be noted that the main controlling factor is the enterprise's potential power costs Z^e, which, in turn, depend on power consumption *RE* and the hourly (time-of-day) tariff *HT* (peak, half-peak or night tariffs).

Let us describe the operation principle of basic blocks of the algorithm (Fig. 2.2). In this block, the operator (for example, the dispatcher) is supposed to set input values of all control parameters (i.e. determine the task – settings). These are designed parameters of iron ore extraction, air supply, ventilation, drainage. If necessary, when operating the algorithm, these tasks can be adjusted by the operator or the ACS.

In block 2, the operating system time of the algorithm is returned to zero: T=0.

Block 3 *Strategy* (r_o, r_w, r_v) starts the procedure (sub-programme) to determine the further control strategy. The algorithm of this procedure is shown below in Fig. 2.2. As parameters are transmitted there, the pair correlation coefficients (r_o, r_w, r_v) are determined between the corresponding control actions and the *RE* parameter being under control. The output of the sub-programme determines a specific control strategy that corresponds to the number of control channels (control actions): 1, 2 or 3. For example, *"for ore", "for ore and water", "for ore, water and ventilation*" respectively. The technique required for making such a choice is given in [13].

Block 4 *Fuzzification* is designed to determine fuzzy variables, therms and membership functions for all corresponding parameters: *O*, *W*, *V*, *RE*, *HT*.

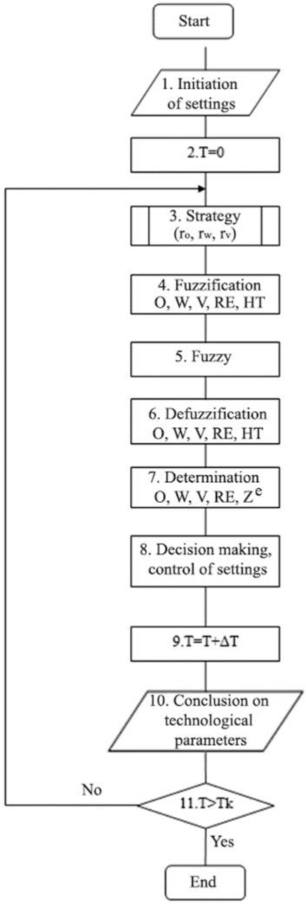


Fig. 2.2 – Algorithm for the FL ACS of electric power consumption

Block 5 provides inference and decision-making procedures based on certain rules below as a result of aggregation, activation and accumulation [142].

Block 6 performs defuzzification (removal of fuzziness) for parameters *O*, *W*, *V*, *RE*, *HT* based on a selected method (e.g. Mamdani, Sugeno, Tsukamoto, Larsen, etc.) [142].

Based on fuzzification data and current values of technological parameters, block 7 calculates evaluative parameters for *O*, *W*, *V*, *RE*, Z^e, followed up by calculation of the required statistics.

Block 8 is designed to automatize the decision-making process, settings control or reset them either manually or automatically.

In block 9, "$T=T+\Delta T$" is adjusted to increase the system time by the value of the sampling step ΔT.

Block 10 visualizes necessary technological parameters on the operator's screen, records current or resulting statistics in a specific database and/or transmits them to the information network, cloud or any other data carriers.

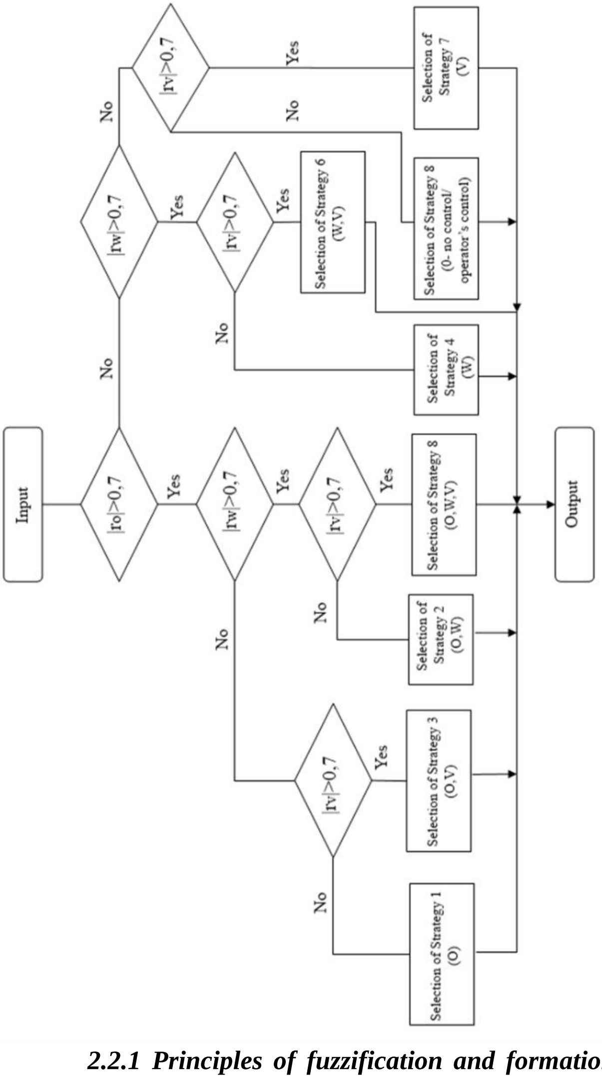
Block 11 compares the current system time (T) and some previously specified operating time of the ACS (T_k). If $T > T_k$, the work of the ACS is over. Otherwise, the operation of the algorithm is looped, starting with the operators of block 3.

Next, let us briefly consider the principle of operation of determining the control strategy based on input correlation dependencies between controlling and controlled parameters. The generalized algorithm of this sub-programme is shown in Fig. 2.3.

As mentioned above, input parameters of the procedure are pair correlation factors (r_o, r_w, r_v) between the corresponding control actions and the controlled *RE* parameter. $|r_{xy}| > 0,7$ is adopted as its threshold value to make decisions about strong relationship between the two factors *XY*. If necessary, the working value for this threshold can be further changed in any direction.

The logic of the algorithm includes a cascade of conditional operators checking the corresponding correlation coefficients between [*O*, *W*, *V*] and [*RE*] (in pairs) followed by an aggregation of "AND/OR" relations. Exceeding the threshold value (i.e. $|r_{xy}| > 0,7$) will mean the need to consider this control channel (or control action) in the resulting strategy.

Thus, the output of the sub-programme defines a specific control strategy that corresponds to the number of control channels (control actions) – 1, 2 or 3, for example, *"for ore"*, *"for ore and water"*, *"for ore, water and ventilation"*, respectively.



2.3 – Algorithm for selecting the control strategy (channels)

2.2.1 Principles of fuzzification and formation of the inference rulebase with single-channel control

This type of control is implemented by one of possible control actions from (2.1). According to the algorithm (Fig. 2.2), these can be strategies 1, 4 or 7. Let us analyze principles of fuzzification of forming of the inference rulebase for single-channel control using Strategy 1 as an example. Other similar strategies are implemented in the same way. The control action here is the ore flow *O*, the controlled parameter is power consumption. Parameters of drainage, air supply and ventilation are classified as disturbing.

According to the method described in [142], we determine a set of fuzzy variables, terms and membership functions and then parameterize the latter. Next, we determine the rulebase for an inference. Finally, you will need to choose a defuzzification algorithm.

We formalize the basic fuzzy set for the system *ACS of electric power consumption*. In our case, this set consists of three elements (N=3):

$$\overline{B}=\bigcup_{i=1}^{N}\left\{\frac{\beta_i}{\mu(\beta_i)}\right\}=\left\{\frac{\beta_1}{\mu(\beta_1)};\frac{\beta_2}{\mu(\beta_2)};\frac{\beta_3}{\mu(\beta_3)}\right\}=\left\{\frac{\beta_{RE}}{\mu(\beta_{RE})};\frac{\beta_{HT}}{\mu(\beta_{FT})};\frac{\beta_P}{\mu(\beta_O)}\right\} \tag{2.2}$$

where $\overline{B}$ is the basic fuzzy set; β_i is a fuzzy value of the determined parameter, e.g. the controlling/controlled one; $\beta_1=\beta_{RE}$ is a corresponding fuzzy value for the power consumption parameter; $\beta_2=\beta_{FT}$ is a fuzzy value for a tariff; $\beta_3=\beta_O$ is a fuzzy value of the ore flow; $\mu(\beta_i)$, $\mu(\beta_1)$, $\mu(\beta_2)$, $\mu(\beta_3)$, $\mu(\beta_{RE})$, $\mu(\beta_{FT})$, $\mu(\beta_O)$ are values of membership functions for corresponding parameters.

We determine linguistic variables (terms) for all the above fuzzy parameters:

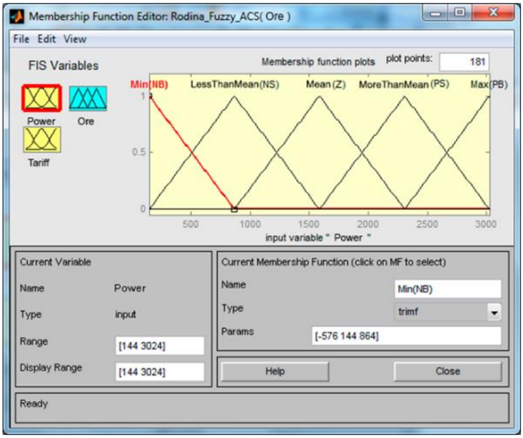
$$T_1^{Power}=\left\{\frac{MIN}{NB};\frac{less\_than\_mean}{NS};\frac{mean}{Z};\frac{more\_than\_mean}{PS};\frac{MAX}{PB}\right\}, \tag{2.3}$$

$$T_2^{Tariff}=\left\{\frac{night}{NS};\frac{shoulder}{Z};\frac{peak}{PS}\right\}, \tag{2.4}$$

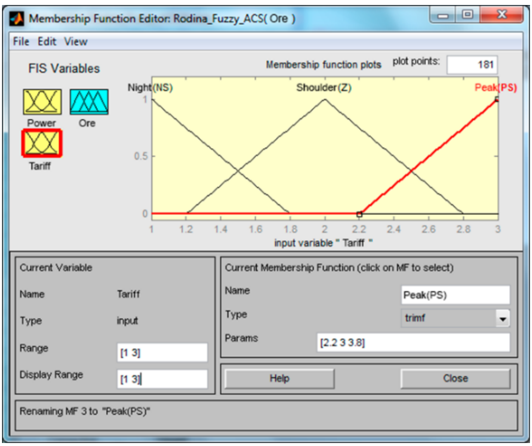
$$T_3^{Ore}=\left\{\frac{MIN}{NB};\frac{less\_than\_mean}{NS};\frac{mean}{Z};\frac{more\_than\_mean}{PS};\frac{MAX}{PB}\right\}, \tag{2.5}$$

where T_1^{Power}, T_2^{Tariff}, T_3^{Ore} are identifiers of numerous terms for fuzzy variables: power consumption, tariff formation and ore flow; {*MIN, less_than_mean, mean, more_than_mean, MAX*}+{*Night, Shoulder, Peak*}, {*NB, NS, Z, PS, PB*}+{*NS, Z, PS*} are complete or shortened identifiers for corresponding values of these terms.n

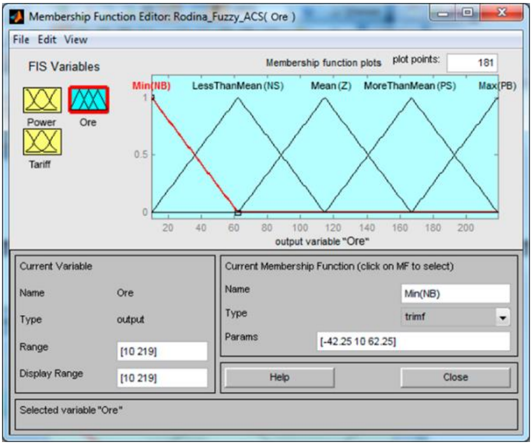
As can be seen from (2.3) – (2.5), a five-digit scale is used for parameters of power consumption and ore flow, and a three-digit scale – for the tariff variable. However, if necessary, quantitative values of all these scales can be changed as follows: to perform fuzzification of all fuzzy set variables (2.2) the standard triangular membership functions are selected. The MATLAB environment is used for parameterization of variables and functions. In Fig. 2.4 an example of such parameterization is shown based on statistics on the Rodina underground mine.



a)



b)



c)

Fig. 2.4 Fuzzification based on statistics of the Rodina underground mine:
a) "Power", b) "Tariff", c) "Ore"

The next step is to define an inference rulebase. Considering the fact that the Mamdani algorithm is planned to be used for defuzzification [142, 143], as well as previously defined fuzzy sets (2.2) and corresponding terms (2.3) – (2.5), the rules of fuzzy inference are formed as follows:

1) IF "Power Consumption" (β_1) = "*MIN*" (*NB*) AND "Tariff" (β_2) = "Peak" (*PS*) THEN "Ore Flow"= "*MIN*" (*NB*);

2) IF "Power Consumption" (β_1) = "Mean" (*Z*) AND "Tariff" (β_2) = "Shoulder" (*Z*) THEN "Ore Flow" = "Mean" (*Z*);

3) IF "Power Consumption" (β_1) = "*MAX*" (*PB*) AND "Tariff" (β_2) = "Night" (*NS*) THEN "Ore Flow" = "*MAX*" (*PB*)

The complete rulebase is shown in Fig. 2.5, as well as in the form of a programme code.

As mentioned above, we adopt the standard Mamdani method for a basic algorithm for defuzzification.

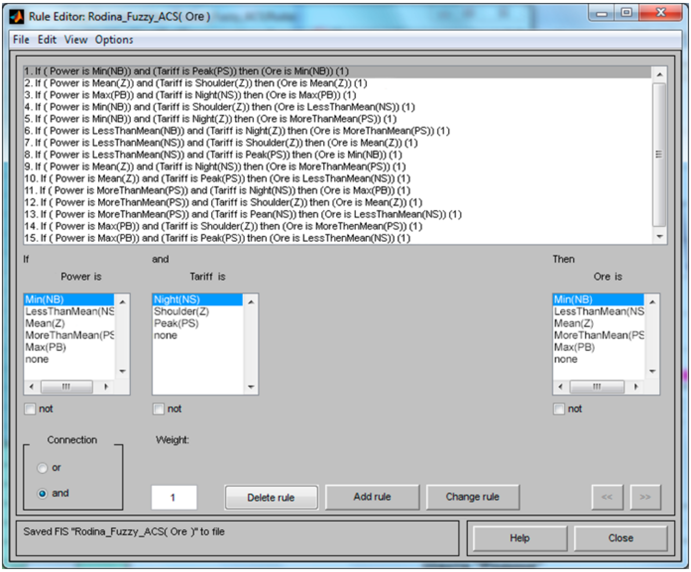


Fig. 2.5 –Formation of the rulebase (15) for decision-making

2.2.2 Principles of fuzzification and formation of the inference rulebase for two-channel control

This type of control is implemented by two of the possible control actions from (2.1). According to the algorithm (Fig. 2.3), these can be strategies 2, 3 or 6. Strategy 2 ("Ore+Drainage") realizes principles of fuzzification and formation of the inference rulebase for two-channel control. Other strategies are implemented in the same way. The control action here is the ore flow O and the volume of drainage W; the controlled parameter is power consumption from (2.1). Parameters of air supply and ventilation are classified as disturbing.

We expand the basic fuzzy set (2.2) to implement two-channel control. In our case, this set now includes four elements (N=4):

$$\overline{B}=\bigcup_{i=1}^{N}\left\{\frac{\beta_i}{\mu(\beta_i)}\right\}=\left\{\frac{\beta_1}{\mu(\beta_1)};\frac{\beta_2}{\mu(\beta_2)};\frac{\beta_3}{\mu(\beta_3)};\frac{\beta_4}{\mu(\beta_4)}\right\}=$$

$$=\left\{\frac{\beta_{RE}}{\mu(\beta_{RE})};\frac{\beta_{FT}}{\mu(\beta_{FT})};\frac{\beta_o}{\mu(\beta_o)};\frac{\beta_w}{\mu(\beta_w)}\right\} \quad (2.6)$$

where $\beta_4 = \beta_w$ is a fuzzy value for drainage; $\mu(\beta_4)$, $\mu(\beta_w)$ is the corresponding value of the membership function.

Then you need to additionally determine the term besides those already defined above (5.13) – (5.15):

$$T_4^{Water} = \left\{ \frac{MIN}{NB}; \frac{less\_than\_mean}{NS}; \frac{mean}{Z}; \frac{more\_than\_mean}{PS}; \frac{MAX}{PB} \right\}, \quad (2.7)$$

where T_4^{Water} is the identifier of the term for the fuzzy variable *drainage volume*.

Taking into account (2.3) – (2.7), we give several examples of forming fuzzy inference rules for this type of control:

1) IF "Power Consumption" (β_1) = «*MIN*» (*NB*) AND "Tariff" (β_2) = "Peak" (*PS*) THEN "Ore Flow"= «*MIN*» (*NB*);

2) IF "Power Consumption" (β_1) = "Mean" (*Z*) AND "Tariff" (β_2) = "Shoulder" (*Z*) THEN "Ore Flow" = "Mean" (*Z*), "Drainage" = "Mean" (*Z*);

3) IF "Power Consumption" (β_1) = «*MAX*» (*PB*) AND "Tariff" (β_2) = "Night" (*NS*) THEN "Ore Flow"= «*MAX*» (*PB*), "Drainage" = "MAX" (*PB*).

Other stages are performed in the above manner.

2.2.2 Principles of fuzzification and formation of the inference rulebase for three-channel control

This type of control is implemented by three control actions from (2.1). In accordance with the algorithm (Fig. 2.3), this is strategy 8 ("Ore +Drainage+Ventilation"). The control action here is the ore flow *O* and the volume of drainage *W* and ventilation *V*, the controlled parameter is power consumption from (2.1). The air supply parameter remains disturbing. Basic fuzzification principles and formation of the inference rulebase for three-channel control are as follows.

The basic fuzzy set (2.16) for possible implementation of three-channel control includes five elements (*N*=5):

$$\overline{B} = \bigcup_{i=1}^{N} \left\{ \frac{\beta_i}{\mu(\beta_i)} \right\} = \left\{ \frac{\beta_1}{\mu(\beta_1)}; \frac{\beta_2}{\mu(\beta_2)}; \frac{\beta_3}{\mu(\beta_3)}; \frac{\beta_4}{\mu(\beta_4)}; \frac{\beta_5}{\mu(\beta_5)} \right\} =$$

$$= \left\{ \frac{\beta_{RE}}{\mu(\beta_{RE})}; \frac{\beta_{FT}}{\mu(\beta_{FT})}; \frac{\beta_o}{\mu(\beta_o)}; \frac{\beta_w}{\mu(\beta_w)}; \frac{\beta_v}{\mu(\beta_v)} \right\} \quad (2.8)$$

where $\beta_5 = \beta_w$ is the fuzzy value for drainage; $\mu(\beta_5)$, $\mu(\beta_v)$ is the corresponding value of the membership function.

Then besides the above terms (2.3) – (2.7), it is necessary to additionally determine the term:

$$T_5^{Ventilation} = \left\{ \frac{MIN}{NB}; \frac{less\_than\_mean}{NS}; \frac{mean}{Z}; \frac{more\_than\_mean}{PS}; \frac{MAX}{PB} \right\} \quad (2.9)$$

where $T_5^{Ventilation}$ is the term identifier for the fuzzy variable *ventilation volume*.

Considering (2.3) – (2.9) we provide several examples of forming fuzzy inference rules for this type of control:

1) IF "Power Consumption" (β_1) = «*MIN*» (*NB*) AND "Tariff" (β_2) = "Peak" (*PS*) THEN "Ore Flow"= «*MIN*» (*NB*), "Drainage" = «*MIN*» (*NB*), "Ventilation" = «*MIN*» (*NB*);

2) IF "Power Consumption" (β_1) = "Mean" (*Z*) AND "Tariff" (β_2) = "Shoulder" (*Z*) THEN "Ore Flow" = "Mean" (*Z*), "Drainage" = "Mean" (*Z*), Ventilation" = "Mean" (*Z*);

3) IF "Power Consumption" (β_1) = «*MAX*» (*PB*) AND "Tariff" (β_2) = "Night" (*NS*) THEN "Ore Flow"= «*MAX*» (*PB*), "Drainage" = "MAX" (*PB*), "Ventilation" = «*MAX*» (*PB*).

Other stages are performed in the above manner.

2.2.4 Methods of determining optimal settings

When using a marginal criterion under restrictions on the main control actions and/or disturbance taking into account functional dependence (2.1) and a zone power tariff, it makes sense to synthesize the appropriate optimal settings. The settings are based on the use of a minimax approach of controlling energy and material flows at underground mines, namely:

– with the maximum (peak) tariff (i.e. β_2 =*PS*), it is desirable to set minimum power consumption by minimizing material flows (ore, water, air, etc.);

– with the minimum (night) tariff (β_2=NS) you can set maximum power consumption due to maximum material flows;

– with the intermediate tariff, if such exists (β_2=Z) we apply balancing power consumption due to corresponding volumes of material flows.

In a similar way, we formalize setting for each possible control channel. So, for the ore flow we have:

$$O_i^* = \begin{cases} \max\left[O_i^{24h}\right], if\ (\beta_2 = NS) \\ \min\left[O_i^{24h}\right], if\ (\beta_2 = PS) \\ K^*\left(\max\left[O_i^{24h}\right] + \min\left[O_i^{24h}\right]\right)\Big/2, if\ (\beta_2 = Z) \end{cases} \tag{2.10}$$

where O_i^* is the value of the setting (task) for ore production at the *i-th* control step (i=1…T^Δ); T^Δ is the number of discrete periods of measuring the parameter (ore) per day (e.g. if we accept periodicity of minimum resolution of the parameter measurements Δt=30 min.=0.5 h, T^Δ=48; $\max\left[O_i^{24h}\right]$, $\min\left[O_i^{24h}\right]$ are maximum and minimum of possible discrete values of ore production per day (of the whole series of measurements); K^* is the correcting factor.

The exact value of the latter can be derived from the balancing daily equation considering the fact that daily ore production should reach a designed level $O_{designed}^{24h}$. In this case

$$O_{designed}^{24h} = \begin{pmatrix} T^{\max} \cdot \max\left[O_i^{24h}\right] + T^{\min} \cdot \min\left[O_i^{24h}\right] + \\ +\tilde{T} \cdot K^*(\max\left[O_i^{24h}\right] + \min\left[O_i^{24h}\right] \end{pmatrix} / 2 \tag{2.11}$$

where $T^{\max}$ is the number of maximum discrete periods with corresponding ore production (i.e. for the night tariff); $T^{\min}$ is the number of minimal periods with corresponding ore production (the peak tariff); $\tilde{T}$ is the number of discrete balancing periods with the intermediate (correcting) production level (the shoulder tariff); $T^{\max}$ + $T^{\min}$ + $\tilde{T}$ =T^Δ, (i=1…T^Δ).

With T^Δ=48, discrete measurements of technological parameters Δt =30min (0.5h) for the current zone tariff of power consumption for industrial enterprises, we obtain: $T^{\max}$=13; $T^{\min}$=14; $\tilde{T}$=21. When substituting these data into (2.11), this results in

$$O_{designed}^{24h} = \begin{pmatrix} 13 \cdot \max\left[O_i^{24h}\right] + 14 \cdot \min\left[O_i^{24h}\right] + \\ +21 \cdot K^*(\max\left[O_i^{24h}\right] + \min\left[O_i^{24h}\right] \end{pmatrix} / 2 \tag{2.12}$$

Hence

$$K^* = \frac{O_{designed}^{24h} - \left(13 \cdot \max\left[O_i^{24h}\right] + 14 \cdot \min\left[O_i^{24h}\right]\right)}{10,5 \cdot \left(\max\left[O_i^{24h}\right] + \min\left[O_i^{24h}\right]\right)} . \tag{2.13}$$

Using similar transformations, there are obtained identical settings like (2.10) and (2.13) for other control channels (water, air, etc.).

$$W_i^* = \begin{cases} \max\left[W_i^{24h}\right], if\ (\beta_2 = NS) \\ \min\left[W_i^{24h}\right], if\ (\beta_2 = PS) \\ K^{**}\left(\max\left[W_i^{24h}\right] + \min\left[W_i^{24h}\right]\right)/2, if\ (\beta_2 = Z) \end{cases} \quad (2.14)$$

where W_i^* is the value of the task (setting) for mine water drainage at the *i-th* control step (i=1…T^{Δ}); $\max\left[W_i^{24h}\right]$, $\min\left[W_i^{24h}\right]$ are maximum/minimum of possible discrete values *mine water drainage per day* (from the whole series of measurements); K^{**} is the correcting factor.

In this case

$$K^{**} = \frac{B_{designed}^{24h} - \left(13 \cdot \max\left[B_{\partial i}^{24h}\right] + 14 \cdot \min\left[B_{\partial i}^{24h}\right]\right)}{10{,}5 \cdot \left(\max\left[B_{\partial i}^{24h}\right] + \min\left[B_{\partial i}^{24h}\right]\right)} \quad (2.15)$$

where $W_{designed}^{24h}$ is designed daily drainage.

It is similar for the ventilation indicator

$$V_i^* = \begin{cases} \max\left[V_i^{24h}\right], if\ (\beta_2 = NS) \\ \min\left[V_i^{24h}\right], if\ (\beta_2 = PS) \\ K^{***}\left(\max\left[V_i^{24h}\right] + \min\left[V_i^{24h}\right]\right)/2, if\ (\beta_2 = Z) \end{cases} \quad (2.16)$$

where V_i^* is a setting for mine air ventilation at the *i-th* control step (i=1…T^{Δ}); $\max\left[V_i^{24h}\right]$, $\min\left[V_i^{24h}\right]$ are maximum/minimum of possible discrete values *mine ventilation per day* (from the whole series of measurements); K^{***} is the correcting factor.

In this case

$$K^{***} = \frac{\tilde{V}_{designed}^{24h} - \left(13 \cdot \max\left[V_i^{24h}\right] + 14 \cdot \min\left[V_i^{24h}\right]\right)}{10{,}5 \cdot \left(\max\left[V_i^{24h}\right] + \min\left[V_i^{24h}\right]\right)} \quad (2.17)$$

where $\tilde{V}_{designed}^{24h}$ is designed daily ventilation.

2.3 Computer modelling of the fuzzy ACS

To model the *ACS of electric power consumption* of an iron ore underground mining enterprise, we will use the Fuzzy Logic Toolbox module

(FLT) from a fairly well-known mathematical package of applications MATLAB. To do this, we use the standard fuzzy modelling method described in [142, 143].

2.3.1 Modelling of single-channel control

The fuzzy controller is built on the basis of single-channel control at the channel "Ore flow – Power consumption" based on statistics of data obtained at the Rodina underground mine (Kryvyi Rih). Taking into account the above fuzzy variables, fuzzy sets (2.2) – (2.5) and membership functions (Fig. 2.6), input and output parameters are specified in the *FIS* editor. As shown above, the Mamdani algorithm is used for defuzzification (Fig. 2.5) [143].

The next step is to determine the rulebase for a fuzzy inference. Examples of these rules are given above, and their full list is shown in Fig. 2.5. It can be shown that similarly you can get other single-channel fuzzy controllers provided by the algorithms in Fig. 2.1, 2.3.

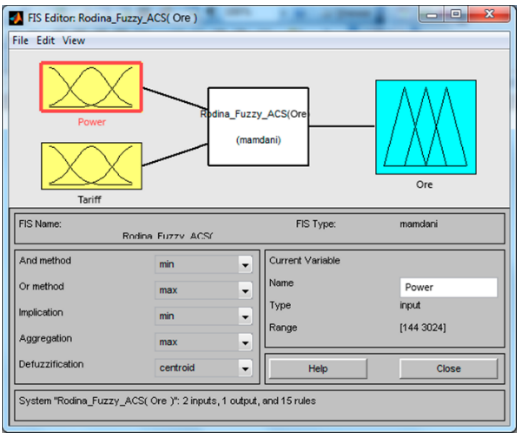


Fig. 2.6 – Creating and defining parameters of a fuzzy single-channel controller

According to this underground mine's statistics there are determined maximum and minimum daily parameters during defuzzification:

– power consumption (144; 3024), kW/day.

– ore production (10; 219), t/day.

The above data enable building a 3D-model of the surface to provide a fuzzy inference of the designed fuzzy model (Fig. 2.7).

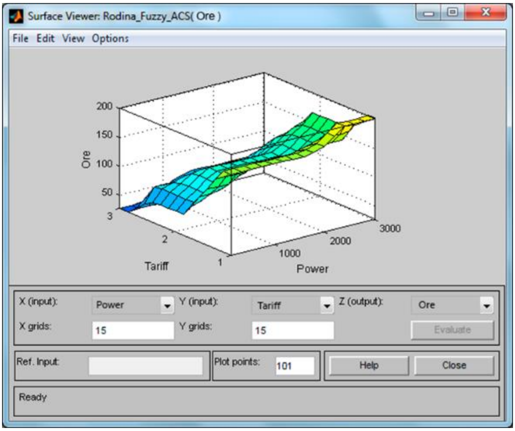
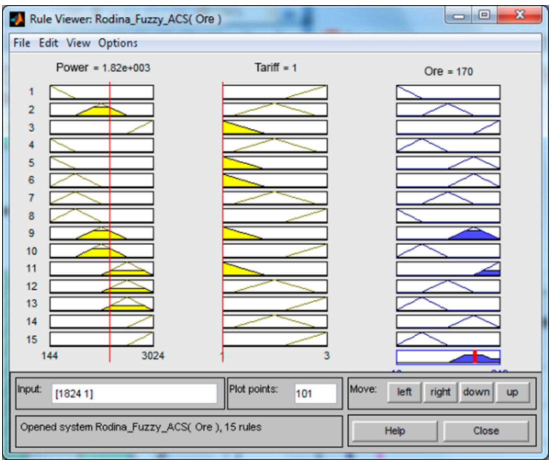
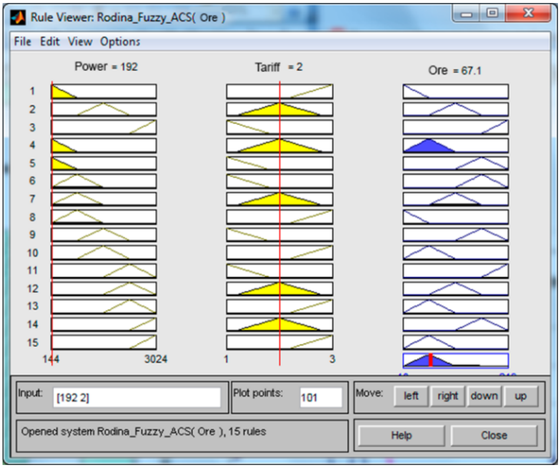


Fig. 2.7 – 3-D model of the surface for the fuzzy inference of the fuzzy model (the Rodina underground mine)

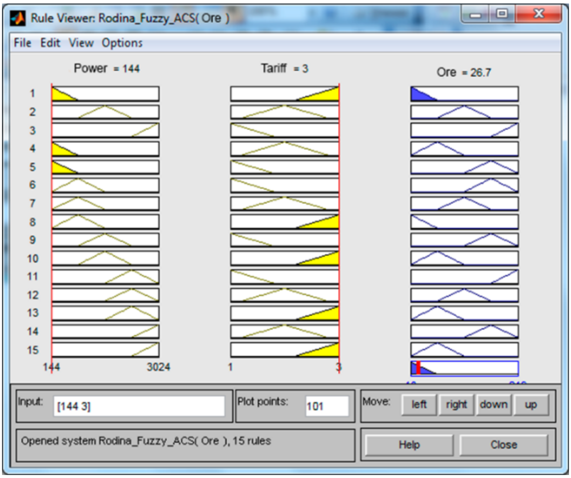
By means of the appropriate *MATLAB FLT* mode for fuzzy inference modelling, we check algorithms (Fig. 2.2) and calculate the expected response of the fuzzy controller to control actions (Fig. 2.8). At the same time, different values of the three-zone power tariff are used.



a)



(b)



(c)

Fig. 2.8 – Fuzzy inference: a) the night tariff (Tariff=1); b) the shoulder tariff (Tariff=2); c) the peak tariff (Tariff=3)

The current data of DTEK Dniprooblenerho (for the first category industrial consumers) are used as basic tariffs [144].

Thus, repeated use of this module enables calculation of all necessary data for further visualization and analysis of corresponding dependences (by ore flows, power consumption, tariffs, costs, etc.).

Fig. 2.9 and Fig. 2.10 show the results of modelling the fuzzy single-channel *ACS of electric power consumption* operated by a single control action – time-distributed daily ore production. The modelling discreteness of the controller is 0.5h = 30 min. The initial data of the underground mine are used to model the process.

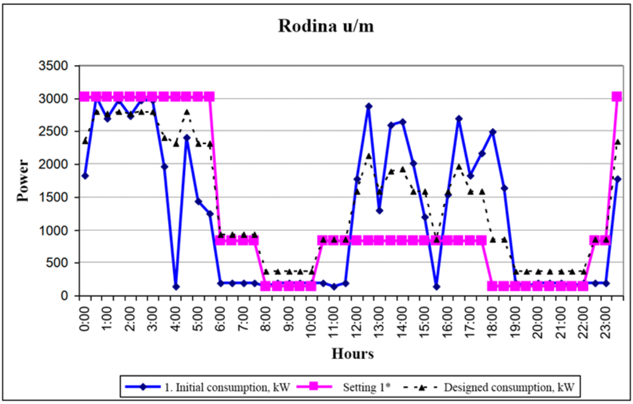


Fig. 2.9 – Dependences of the consumed capacity of active power (1), the optimal setting of type 1* (2.20) and the designed power consumption with minimax control

Analysis of modelling results from Fig. 2.10 and Fig. 2.11 and analytical calculations show that the use of minimax criteria of type (2.1) - (2.2) at the Rodina underground mine allows an increase of daily ore production by 14.85% (i.e. over 600t/day). At the same time, daily power consumption will similarly increase by 14.86% (considering the high correlation coefficient of about 0.9 [13]), and power costs will increase by 10.83% (8 thousand UAH) taking into account the zone tariff. However, with the current costs for iron ore materials on the world market of about 110$/t [3, 4], this can be compensated by a potential income of about 1.782M UAH/day (with 27UAH for 1USD).

Optimal settings (1*, 2*) obtained from expressions (2.10) and criteria allow maintaining designed daily ore production, but due to a more efficient time redistribution of power consumption (zone tariffs) power costs can be reduced by 27.51% per day.

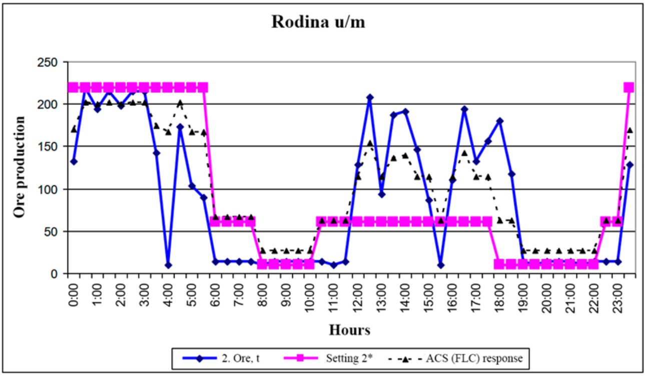


Fig. 2.10 – Dependences of ore flow (2) as a control channel, fulfillment of the optimal setting of type 2* (2.10) and designed production provided that the latter is maximized (i.e. minimax control) by the criterion of type (2.2)

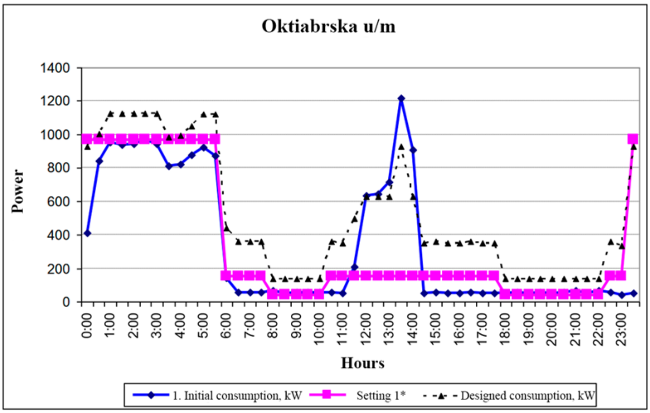


Fig. 2.11 – Dependences of the consumed capacity of active power (1), development of the optimal setting of type 1* (2.10) and the designed power consumption with minimax control

Similar costs and the modelling for the Oktiabrska underground mine reveal identical trends, namely, the minimax approach enables an increase of daily iron ore production by 52.40% (i.e. over 1500t/day). At the same time, daily power consumption will similarly increase by 52.6%, and power costs will increase by 75.31% (over 10 000UAH), taking into account the three-zone tariff. However, at the current price for marketable iron ore on the world market of about 110$/t [3, 4], this can be compensated by a potential income of about 4.455M UAH per day (with 27UAH for 1USD).

Optimal settings (1*, 2*) obtained from expressions (2.10) and criteria allow maintaining designed daily ore production, but due to a more efficient time redistribution of power consumption (zone tariffs) power costs can be reduced by 20.24% per day.

Fig. 2.11 and Fig. 2.12 show the corresponding dependences that demonstrate quality of fulfilling control tasks.

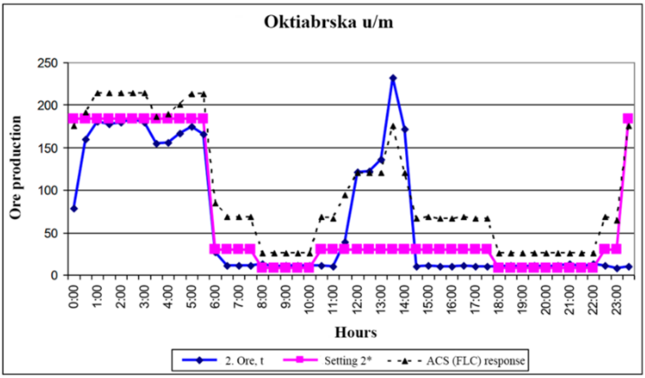


Fig. 2.12 – Dependences of ore flow (2) as a control channel, fulfillment of the optimal setting of type 2* (2.10) and designed production provided that the latter is maximized (i.e. minimax control)

2.3.2 Modelling of multichannel control

Basic principles of building fuzzy controllers (including fuzzification, fuzzy inference, defuzzification, etc.) and algorithms for their operation in multi-channel control are described above. In this section, we present the results of modelling automated control of energy consumption on the example of two channels ("Ore …", "Water…") (Fig. 2.13) and three channels ("Ore…", "Water…", "Air…"). Main calculations are based on statistics of the Rodina underground mine. Yet, as analysis reveals, with this methodology, the results can be similarly reproduced for all algorithm strategies (Fig. 2.3, 2.4) and at other underground mining enterprises (mines).

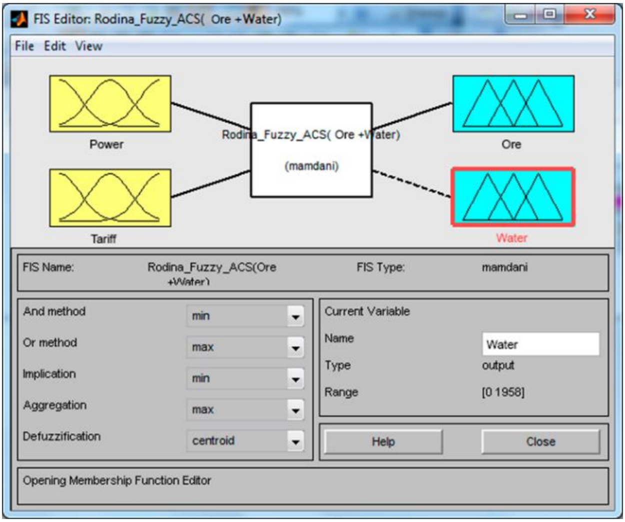


Fig. 2.13 – Structure of the two-channel Fuzzy-controller ("Ore-Water")

Therefore, implementation of the channel "Ore" control in MATLAB using the structure of the controller with original data shows results similar to Fig. 2.12. The "Water" channel minimax control and that of type (2.14) are shown in Fig. 2.14. The response of the total power consumption (as a controlled parameter) as a result of the fuzzy ACS power consumption and the optimal insertion 12* is in Fig. 2.15.

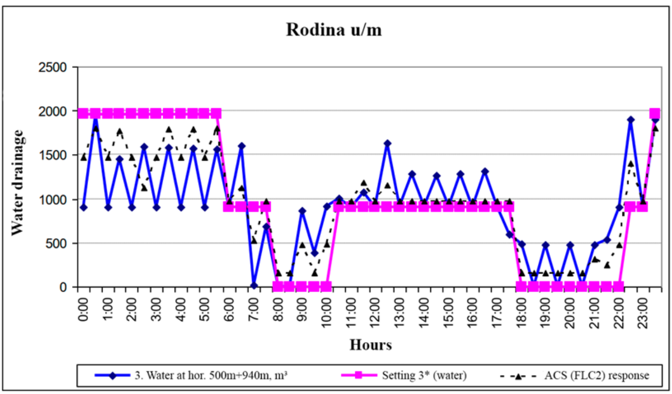


Fig. 2.14 – Modelling of minimax optimal control for the "Water" channel

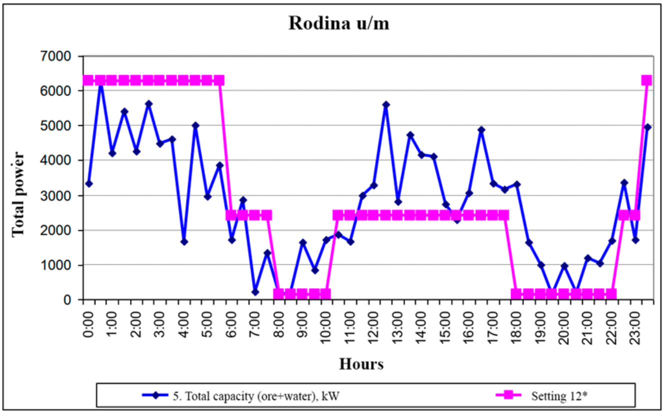


Fig. 2.15 – Results of the two-channel ("Ore+Water") control over total power consumption at Rodina underground mine on the basis of the optimal setting ("Setting 12*")

Results of analyzing other calculated values reveal:

1. Minimax control (reduction of power consumption with maximized ore production) for the channel "Water" will lead to the designed increase in daily power consumption by about 1.5%, which, as shown above, is fully compensated by increased daily ore production and potential income from subsequent sales.

2. Setting 12*-based control of type (2.14) will maintain designed daily ore production, but the total daily cost of power consumption will drop by 28.39% due to more efficient distribution of ore/water flows and corresponding power consumption for a technological stage for the three-zone tariff.

Fig. 2.17 shows a block diagram of a two-channel Fuzzy-controller ("Ore-Water-Air"), which is implemented through using basic principles, algorithms and rules set out earlier.

Given the fact that the control based on two first channels ("Ore-Water") is completely identical to those already described and demonstrated earlier, we will further limit the results of computer modelling by the third channel "Air" (Fig. 2.17) and total power consumption (Fig. 2.18) for all three technological stages (i.e. extraction, drainage, ventilation).

Results of analyzing obtained dependences reveal:

1. Minimax control (reduction of power consumption with maximized ore production) for the channel "Water" will lead to the designed

increase in daily power consumption by about 4.3%, which, as shown above, is fully compensated by increased daily ore production and potential income from subsequent sales.

2. Setting 123*-based control of type (2.14) and (2.16) will maintain the designed daily ore production, but the total daily cost of power consumption will drop by 16.23% due to more efficient distribution of ore/water flows and corresponding power consumption for a technological stage for the three-zone tariff.

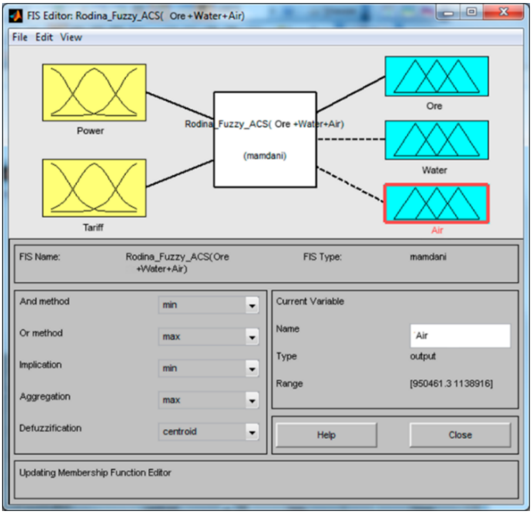


Fig. 2.16 – Two-channel Fuzzy-controller ("Ore-Water-Air")

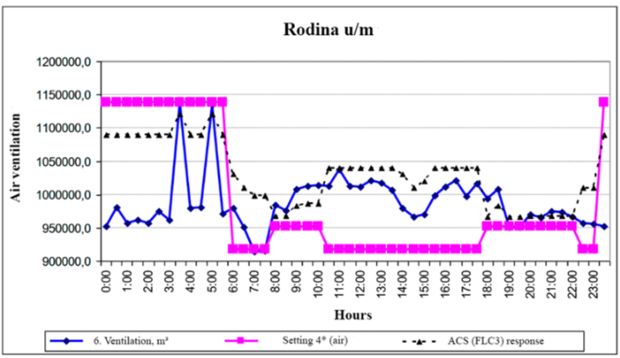


Fig. 2.17 – Modelling of minimax optimal control
for the channel "Air" ("Air ventilation")

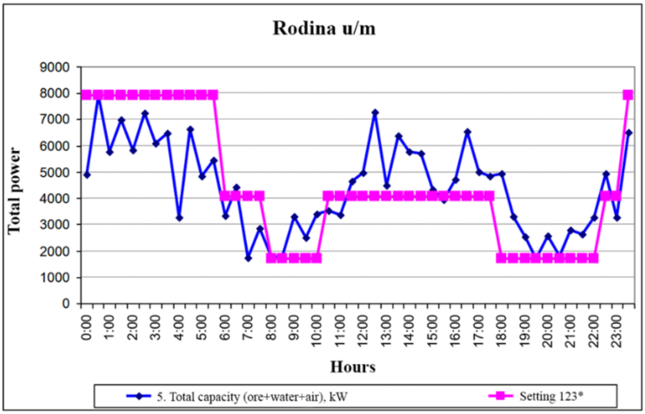


Fig. 2.18 – Results of the three-channel ("Ore-Water-Air") control over total power consumption at Rodina underground mine on the basis of the optimal setting ("Setting 123*")

2.4 Development of the FL-based control algorithm

2.4.1 Principles of fuzzification and formation of the logic inference rulebase for single-channel control (two-tariff "Night/Peak" case)

Let us determine sets of linguistic variables (terms) for all the above fuzzy parameters:

$$T_1^{Power} = \left\{ \frac{MIN}{NB}; \frac{Mean}{Z}; \frac{MAX}{PB} \right\}, \tag{2.18}$$

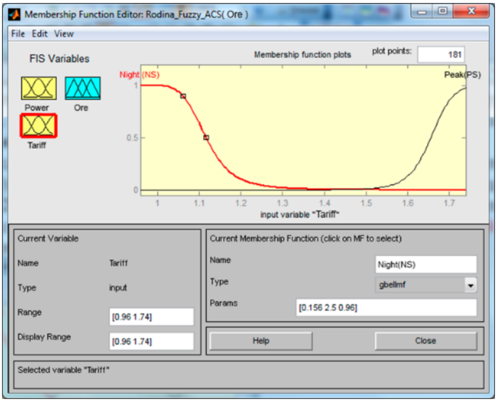
$$T_2^{Tariff} = \left\{ \frac{Night}{\mathrm{NS}}; \frac{Peak}{\mathrm{PS}} \right\}, \tag{2.19}$$

$$T_3^{Ore} = \left\{ \frac{MIN}{NB}; \frac{Mean}{Z}; \frac{MAX}{PB} \right\}, \tag{2.20}$$

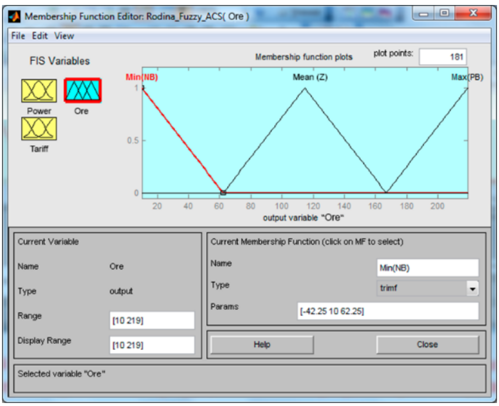
where T_1^{Power}, T_2^{Tariff}, T_3^{Ore} are multiple term identifiers for fuzzy variables – power consumption, tariff formation and ore flow; {*MIN*, *mean*, *MAX*}+{*Night*, *Peak*}, {*NB*, *Z*, *PB*}+{*NS*, *PS*} are complete or shortened identifiers to denote corresponding values of the terms.

As can be seen from (2.18) - (2.20), a three-digit scale is used for parameters of power consumption and ore flow while a two-digit scale – for the tariff variable. However, if necessary, quantitative values of all these scales can be changed in any direction. Subsequently, the standard triangular membership functions are chosen for fuzzification of fuzzy variables of (2.18) and (2.20), and the tangential one – for (2.19).

Parameterization of data of variables and functions is performed in MATLAB. Fig. 2.19 shows an example of parameterization based on the Rodina underground mine statistics.



a)



b)

Fig. 2.19 – Fuzzification based on data from the Rodina underground mine by parameters of power consumption: a) the tariff (two-zone), b) ore production

Fuzzy sets (2.18) and relevant conditions (2.19), (2.20) of fuzzy inference rules will be formed as follows:

1) IF "Power consumption" (β_1) = "*MIN*" (NB) AND "Tariff" (β_2) = "Peak" (PS) THEN "Ore flow" = "*MIN*" (NB);

2) IF "Power consumption" (β_1) = "*MAX*" (PB) AND "Tariff" (β_2) = "Night" (NS) THEN "Ore flow" = "*MAX*" (PB).

Fig. 2.20 gives the complete base of these rules.

As mentioned above, we use the standard Mamdani method as a basic algorithm for the subsequent defuzzification procedure.

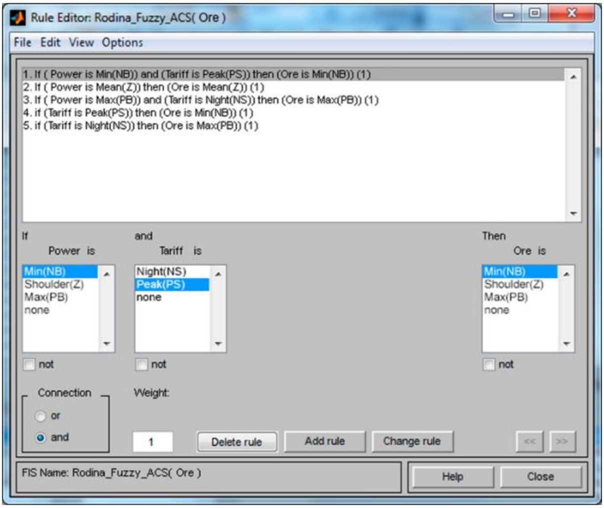


Fig. 2.20 – Formation of the rulebase (5) for decision-making

2.4.2 Principles of fuzzification and formation of the logic inference rulebase for two-channel control (two-tariff case)

This type of control is implemented by two of possible control actions from (2.1). According to the algorithm (Fig. 2.3), this can be strategies 2, 3 or 6. General principles of fuzzification and formation of the logic inference rulebase for two-channel control are exemplified by strategy ("Ore+Drainage"). Other strategies of this type will be implemented similarly. Ore flow O and drainage water W are control actions here, while power consumption from is a controlling parameter. Parameters of air supply and ventilation are disturbing.

We extend basic fuzzy sets (2.18) - (2.20) to implement two-channel control. We define the following term:

$$T_4^{Water} = \left\{ \frac{MIN}{NB}; \frac{Mean}{Z}; \frac{MAX}{PB} \right\}, \qquad (2.21)$$

where T_4^{Water} is a term identifier for the fuzzy variable of water drainage.

Considering (2.18) and (2.21), below are examples of formation of fuzzy inference rules for this type of control:

1) IF "Power consumption" (β_1) = "*MIN*" (NB) AND "Tariff" (β_2) = "Peak" (PS) THEN "Ore flow" = "*MIN*" (NB), "Drainage" = "MIN" (NB);

2) IF "Power consumption" (β_1) = "*MAX*" (PB) AND "Tariff" (β_2) = "Night" (NS) THEN "Ore flow" = "*MAX*" (PB), "Drainage" = "*MAX*" (PB).

Other stages are performed similarly to the above case described in 2.2.2.

2.4.3 Principles of fuzzification and formation of the logic inference rulebase for three-channel control (two-tariff case)

This type of control is implemented by three control actions from (2.1). In accordance with the algorithm (Fig. 2.4), this is strategy 8 ("Ore + Drainage + Ventilation"). The control actions are ore flow *O* and water drainage *W* and ventilation *V*, the control parameter is the value of power consumption from (2.1). The air supply parameter remains disturbing. General principles of fuzzification and formation of the logic inference rulebase for three-channel control are as follows.

Besides the term sets already defined above (2.18) - (2.21) we define the following term:

$$T_5^{Ventilation} = \left\{ \frac{MIN}{NB}; \frac{Mean}{Z}; \frac{MAX}{PB} \right\}, \qquad (2.22)$$

where $T_5^{Ventilation}$ is a term identifier for the fuzzy variable of ventilation.

Considering (2.18) - (2.22), below are examples of formation of fuzzy inference rules for this type of control:

1) IF "Power consumption" (β_1) = "*MIN*" (NB) AND "Tariff" (β_2) = "Peak" (PS) THEN "Ore flow" = "*MIN*" (NB), "Drainage" = "*MIN*" (NB), "Ventilation" = "MIN" (NB);

2) IF "Power consumption" (β_1) = "*MAX*" (PB) AND "Tariff" (β_2) = "Night" (NS) THEN "Ore flow" = "*MAX*" (PB), "Drainage" = "*MAX*" (PB), "Ventilation" = "*MAX*" (PB);

Other stages are performed similarly to the above case described in 2.2.3.

2.4.4 Computer modelling of the fuzzy ACS

To model the operation of the ACS of electric power consumption of an underground mining enterprise, we use the Fuzzy Logic Toolbox (FLT) from the well-known mathematical software package MATLAB. To do this, we use the standard fuzzy modelling technique described in [142].

2.4.5 Modelling of single-channel control (two-tariff case)

The fuzzy controller is built on the basis of single-channel control for the channel "Ore flow – >Power consumption" with statistics from the Rodina underground mine (Kryvyi Rih).

Input and output parameters are specified through considering the above fuzzy variables, fuzzy sets (2.18) - (2.20) and membership functions in the FIS editor. As shown above, the Mamdani algorithm is used for the following defuzzification.

According to statistics, during fuzzification, the following maximum and minimum daily parameters are determined:

– power consumption (144; 3024), kW/day;

– ore production (10; 219), t/day.

These data enable building a 3D-surface model for fuzzy inference of the developed fuzzy model (Fig. 2.21).

The next step is to determine the rulebase for the fuzzy inference. Examples of these rules are given above (2.2.1), and their list is shown in Fig. 2.22.

Using the appropriate MATLAB FLT mode to model fuzzy inference procedures, we check algorithms (Fig. 2.2) and calculate the expected response of the fuzzy controller to control actions (Fig. 2.22). At the same time, different values of the two-zone tariff for power consumed are used. The current data of DTEK Dniprooblenerho (for the first category industrial consumers) [146] are taken for basic tariffs.

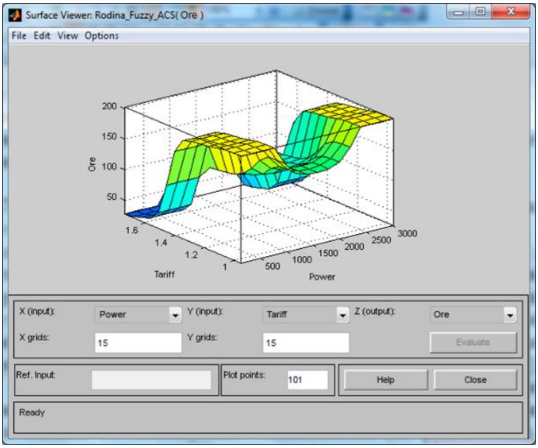
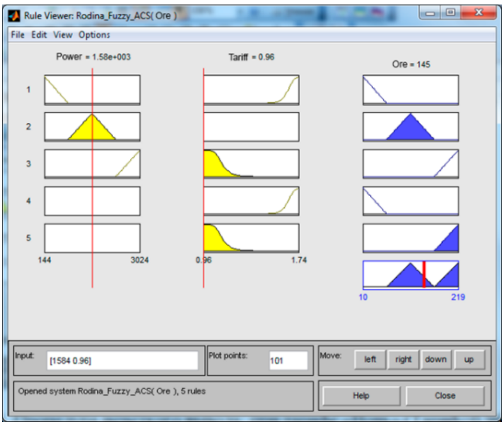
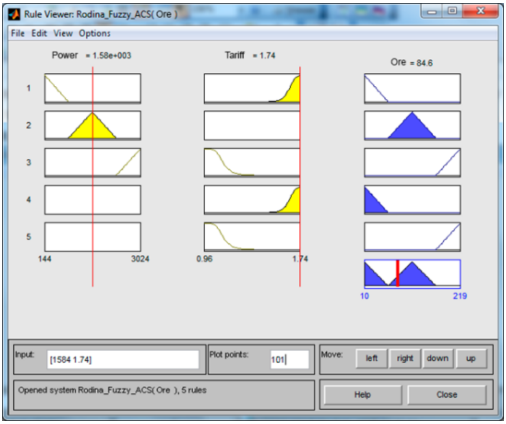


Fig. 2.21 – 3D surface model of the fuzzy inference of the fuzzy model (the Rodina underground mine for the two-zone tariff)

Thus, all the necessary data for subsequent visualization and analysis of relevant dependencies (ore flows consumed, power consumption, tariffs, costs, etc.) is calculated on the basis of multiple application of this module.



a)



b)

Fig. 2.22 – Fuzzy inference: a) for the tariff "Night" (Tariff= 0.96); b) for the tariff "Peak" (Tariff=1.74)

The results of modelling the fuzzy single-channel *ACS of electric power consumption* on the basis of a single control action – daily time distributed ore production – are shown in Fig. 2.23 and Fig. 2.24. The discreteness of the controller's modelling is 0.5h = 30min. In the course of modelling, the initial data of the underground mine are used.

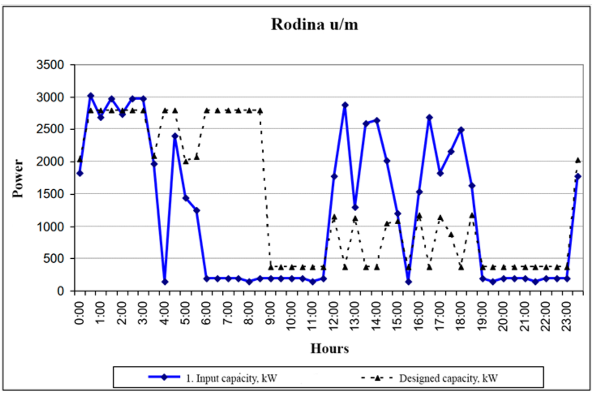


Fig. 2.23 – Dependences of consumed capacity of active power and designed power consumption with minimax control

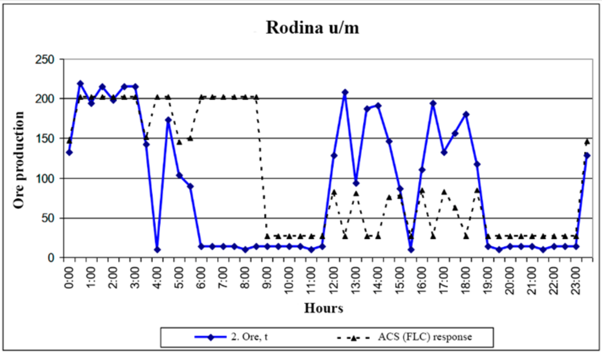


Fig. 2.24 – Dependences of ore flows as a control channel and designed power consumption with maximization of the latter by the criterion of type (5.4)

Analysis of the modelling results of Fig. 2.23 and Fig. 2.24 shows that the two-zone tariff causes an increase in power costs by 12.88% (without the ACS). Application of the ACS with the fuzzy controller (FLC) based on the minimax criteria of types (2.1) and (2.2) at the Rodina underground mine allows increasing daily ore production by 11.9% (i.e. by over 506t per day). Yet, daily power consumption will similarly increase by 11.9%, and power costs will decrease by 4.31%, taking into account the two-zone tariff due to more efficient time redistribution of ore flows. However, this is still 8.57% worse than when using the three-rate tariff discussed above.

Unfortunately, the use of optimal settings obtained from expressions (2.10) and criteria for the two-zone tariff is impossible. Therefore, comparative studies for this case are not carried out.

2.4.6 Modelling of multichannel control (two-tariff case)

Basic principles of building fuzzy controllers (including fuzzification, fuzzy logical inference, defuzzification, etc.), as well as algorithms for their work in multi-channel control are described above. In this subsection we present the results of modelling automated power control on the example of two channels ("Ore...", "Water...") and three channels ("Ore...", "Water...", "Air...").

Major calculations are carried out with statistics from the Rodina underground mine. However, as the analysis shows, using this methodology, these results can be similarly reproduced for all algorithm strategies (Fig. 2.1 and 2.2) and at other underground mining enterprises.

Thus, implementation of the “Ore” channel control in the MATLAB environment by using the controller with the underground mine's initial data reveals results similar to those in Fig. 2.25. Fig. 2.26 shows minimax control implementation for the "Water" channel. Modelling discreteness of the controller is *T*=30min. In the course of modelling, the initial data of the mine are used.

The final response of the total power consumption (as a controlled parameter) in conditions of the fuzzy ACS is shown in Fig. 2.26. Modelling discreteness of the controller is *T*=30 min.

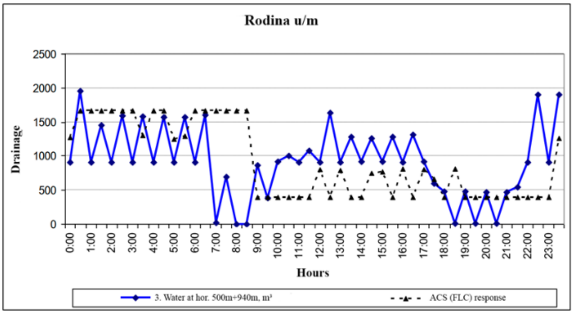


Fig. 2.25 – Modelling of minimax control for the "Water" channel for the time-of-day tariff

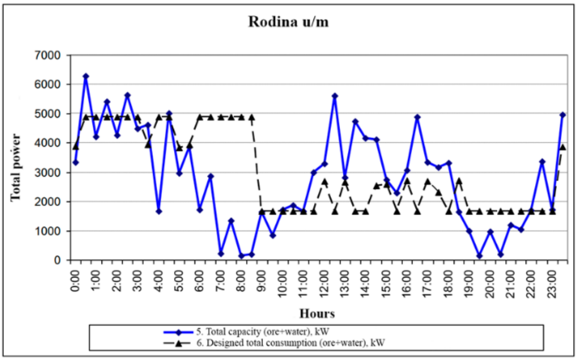


Fig. 2.26 – Results of two-channel ("Ore+Water") control of total power consumption at the Rodina underground mine for the time-of-day tariff

The results of calculations analysis show that with the time-of-day tariff (compared to the three-rate tariff considered above), daily power costs increase by 7.1%.

Minimax control of the “Water” channel (reduced power consumption with maximized ore production) will lead to an increase in designed daily power consumption by about 6.97%.

As shown above, this is fully compensated by an increase in daily ore production (approximately +508t per day) and a potential income from further sale.

Fig. 2.16 demonstrates a diagram of the three-channel fuzzy controller ("Ore-Water-Air"), which is implemented by using basic principles, algorithms and rules presented above (2.2.3).

Considering the fact that implementation of the first two control channels regulation ("Ore-Water") is completely similar to that presented and demonstrated earlier, we will limit ourselves only to the third "Air" channel (Fig. 2.27) and total power consumption (Fig. 2.28) for all three technological stages (ore production, drainage, ventilation) when providing the results of computer modelling.

The analysis results of the obtained dependences show that, unlike single- and two-channel control with the two-zone tariff for power consumption, minimax control (minimized power consumption with maximized ore production) will cause a designed increase in daily power consumption by about 4.45%. However, this is fully compensated by an increase in daily ore production and a potential income from further sale.

The total daily costs of power consumed will be reduced by 2.5% due to a more efficient distribution of ore-water flows and corresponding power consumption at technological stages with the time-of-day tariff.

Thus, three-channel fuzzy control over ore flows, drainage and ventilation is the most effective way to conduct underground iron ore mining, even in conditions of using the time-of-day (hourly) tariff.

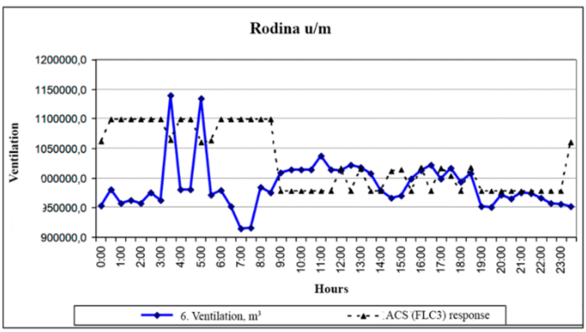


Fig. 2.27 – Modelling of minimax control for the "Air" ("Ventilation") channel for the time-of-day tariff

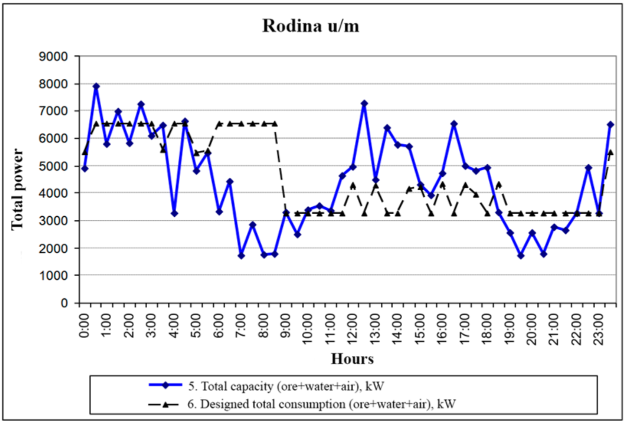


Fig. 2.28 – Results of three-channel ("Ore-Water-Air") control of total power consumption at the Rodina underground mine for the time-of-day tariff

2.5 Building a generalized algorithm of power consumption control with time-of-day tariffs and constraints

As mentioned in 2.1, payment schedules for power consumed by industrial enterprises change at the state regulatory level.

It is logical to expect such changes in the future. Therefore, the need to predict and determine prospects of this process and development of tactics for the ACS functioning, or, more precisely, adjustment of its correcting algorithm to conditions with new input data is what the presented research is aimed at.

This aim can be implemented through building a generalized algorithm of the ACS over power flows for the following two cases:

1 a selected tariff with constraints for daily power consumption with regard to contracts or

2. a changeable tariff (e.g. hourly/daily) similar to that in Fig. 2.1.

1. Algorithm (Fig. 2.29). Block 1 informs about the start of functioning.

Block 2 actualizes the current regulatory base of Ukraine for power consumption and supply. Here, initial information on current parameters is input according to current criteria of control and problem statement (2.23-2.32).

Conditional block 3 checks whether the enterprise has a valid contract with the power generating company for power supply. If there is such a contract, the algorithm continues from the next block (4). Otherwise (there is no contract) this algorithm is terminated, and further calculations can be made on a general basis or one should initiate contract conclusion in the future.

Similarly, conditional block 4 checks whether the enterprise has a valid contract with a power transporting company for power transportation. If there is such a contract, the algorithm continues from the next block (5). Otherwise (there is no contract) this algorithm is terminated, and further calculations can be made on a general basis or one should initiate contract conclusion in the future.

Block 5 enables selection of a category of industrial consumers (categories "A" or "B" now), i.e. Category = {"A", "B"}.

In block 6, it is envisaged for the enterprise to select (order from the power generating company) a daily tariff (Td) and designed power consumption volume. It is desirable to observe the ordered volume as accurately as possible, because a shortfall or vice versa, exceeding the ordered volume may entail potential economic losses of the enterprise.

Following the requirements for the declared power consumption, a comprehensive estimate indicator (T_Σ) is formed in block 7, taking into account the actual power consumption and a special function "Penalty". A useful property of the latter is that the value of the penalty should approach 0 ("no penalty" or it is minimal), if there are no deviations. Otherwise (positive or negative deviation), the function begins to increase sharply (i.e., the "penalty" is maximized). An example of a penalty function is

$$f^{penalty} = r\sum_{i=1}^{NS}\left[\frac{\left|\overline{T}_i - T_i^{permissible\ value}\right| + (\overline{T}_i - T_i^{permissible\ value})}{2}\right]^2, \quad (2.23)$$

where $\overline{T}_i$ is a daily average of the i-th tariff; $T_i^{\partial on.}$ is a constraint on deviations in power consumption when applying the i-th tariff in the system; NS is the number of established tariff intervals; r is the penalty factor (an integer chosen empirically).

$$I = \left[Ed + f^{penalty}(\mathrm{T}d, RE, HT)\right] \to MIN, \quad (2.24)$$

where I is a resulting function of the aim; Ed is the estimate of the actual power consumption; Td is the tariff.

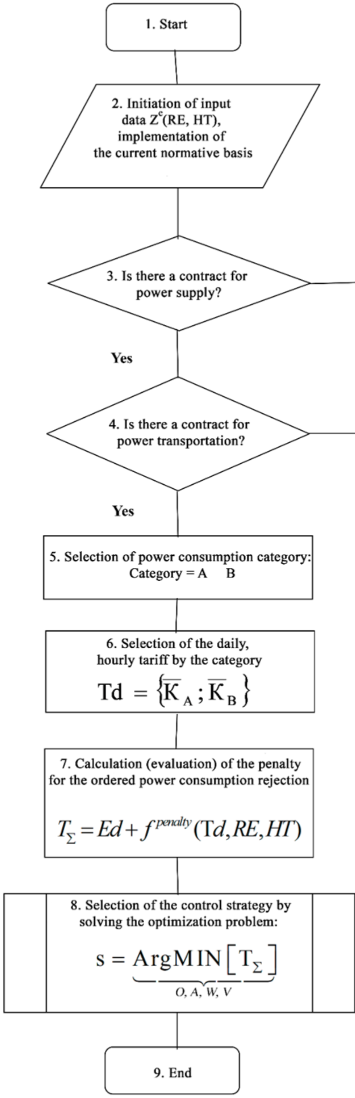


Fig. 2.30 – General algorithm of the ACS operation with the constrained selective tariff with constraints

Block 8 is actually designed to select the optimal strategy (s) for controlling power consumption through solving an optimization problem with certain parameters of state vectors. Taking into account the basic algorithms (Fig. 2.30, Fig. 2.31), parameters of ore flows, air, drainage and ventilation (O, A, W, V) with which the minimum value of the target functional of type (2.24) is achieved will become a solution to the problem

$$\mathrm{s} = \underbrace{\mathrm{ArgMIN}\left[I\right]}_{O,A,W,V}, \qquad (2.25)$$

where s is the number of the optimal control strategy according to the algorithm (Fig. 2.31).

Final block 9 of the algorithm actually stops the corresponding calculation and allows further implementation of more complex smart approaches to energy control.

$$\mathrm{Z}^{\mathrm{e}} = F\left(RE, HT\right) \Rightarrow \min, \qquad (2.26)$$

$$\mathrm{O} \Rightarrow \max, \qquad (2.27)$$

$$\mathrm{A} \Rightarrow \max, \qquad (2.28)$$

$$W \Rightarrow \max, \qquad (2.29)$$

$$V \Rightarrow \max, \qquad (2.30)$$

where Z^{e} is total power costs (hourly, daily), UAH; RE is power consumption (hourly, daily); HT is the current tariff, UAH/kW; $F(\cdot)$ is a determined functional dependence; O is ore production (hourly, daily), t; A is air delivery (hourly, daily), m3; W is water drainage volume, m3; V is ventilation (hourly, daily), m3.

Given the potential complexity of solving such multi-criteria problems, some of the above minimax criteria can be replaced with the following constraints:

$$\mathrm{O} \geq \mathrm{O}^{\min}, \qquad (2.31)$$

$$\mathrm{A} \geq \mathrm{A}^{\min}, \qquad (2.32)$$

$$W \geq \mathrm{W}^{\min}, \qquad (2.33)$$

$$V \geq \mathrm{V}^{\min}, \qquad (2.34)$$

where $\mathrm{O}^{\min}$, $\mathrm{A}^{\min}$, $\mathrm{W}^{\min}$, $\mathrm{V}^{\min}$ are margin values of the corresponding parameters (e.g. designed daily values).

Power consumption in the system as a whole or at separate stages from the local criterion of target function (4) can be redefined as

$$RE = f\left(O, A, W, V\right), \tag{2.35}$$

where $f(\cdot)$ is either a function or approximation.

2. Development of the FL-based algorithm for power consumption control. Modern smart approaches to implementing FL-based automated control are rather promising, taking into account the above prerequisites in conditions of nonlinear characteristics, incomplete information, multi-channeling in real production situations [6-7].

These approaches enable development and implementation of algorithms for a fuzzy control system (Fig. 2.3, 2.4) with several control strategies (i.e. multi-channeling), namely:

$$\mathrm{S} = \left\{O, O+V, O+W, V, 0, W+V, W, O+V+W\right\}. \tag{2.36}$$

Each strategy conditions the number of possible control actions (control channels) that are to be further implemented in the ACS. For example, according to (14), the number of such parameters can be 0 (no control or "manual mode"), 1, 2 or 3. However, it should be noted that using this technique, the number of channels can be further increased if necessary.

It should also be noted that according to (2.26) and (2.27), the main controlled factor is power potential Z^e costs of the enterprise, which in turn depend on power consumption RE and the tariff HT.

The algorithms include a number of conditionals checking correlation coefficients between [O, W, V] and [RE] (in pairs) followed by aggregation of connectives of type "AND/OR". Exceeding the threshold ||rxy>0.7| means the need to consider this control channel (or control action) as a resulting strategy. Thus, the output determines a specific control strategy that corresponds to the number of control channels – 1, 2 or 3, e.g. "Ore", "Ore, Water", "Ore, Water and Ventilation".

3. The second case advanced at the beginning concerns the "floating" daily tariff, which changes every hour, i.e. NS=24 in accordance with (2.23) and (2.24). It also has a constraint on power consumption; the exceeded power consumption itself and also the reduced one are undesirable ("penalized").

The conducted analysis shows that for this case, it is advisable to take the value of specific power consumption as a basic indicator of the target function (2) per 1t of mined ore, i.e., considering (2.26) - (2.30)

$$I = \frac{RE}{O} + f^{penalty}(RE, HT), \tag{2.37}$$

where $RE = \{E_1, E_2, ..., E_{24}, E_\Sigma, E_\Sigma^{permissible\ value}\}$ is a set of power consumption indicators in the 1st, 2nd, …, 24th hour; $E_\Sigma = E_1 + E_2 + ... + E_{24}$ is total power consumption per day; $E_\Sigma^{permissible\ value}$ is a constraint on daily consumption (actual order); $O = \{O_1, O_2, ..., O_{24}, \overline{O}\}$ is a set of ore production indicators (hourly in the 1st, 2nd, …, 24th hour), $\overline{P}$ is average daily production; $HT = \{T_1, T_2, ..., T_{24}, \overline{T}\}$ are power time-of-day tariffs (hourly in the 1st, 2nd, …, 24th hour), $\overline{P}$ is an average daily tariff.

In this case, we can apply the following expression for the penalty function

$$f^{penalty}(RE, HT) = r\frac{\overline{T}}{\overline{\overline{P}}}\sqrt{\left[\frac{\left|E_\Sigma - E_\Sigma^{permissible\ value}\right| + \left(E_\Sigma - E_\Sigma^{permissible\ value}\right)}{2}\right]^2} \quad . \quad (2.38)$$

Considering this, we obtain the final expression for the target function

$$I = \left[\frac{1}{24}\sum_{i=1}^{24}\frac{E_i \cdot T_i}{P_i} + r\frac{\overline{T}}{\overline{\overline{P}}}\sqrt{\left[\frac{\left|E_\Sigma - E_\Sigma^{permissible\ value}\right| + \left(E_\Sigma - E_\Sigma^{permissible\ value}\right)}{2}\right]^2}\right] \to MIN \quad .(2.39)$$

Some vectors O^*, E^* of ore production indicators and the corresponding power consumption of the following type are the solution to the target function

$$O^* = \{O_1, O_2, ..., O_{24}\}$$
$$E^* = \{E_1, E_2, ..., E_{24}\} \quad . \quad (2.40)$$

Besides, as proven in [1], there is a close correlation between production and power consumption at many deposits. Therefore, it is possible to calculate those indicators by using established regression equations as follows

$$O_i = f_{\beta oe}(E_i)$$
$$E_i = f_{\beta eo}(O_i) \quad , \quad (2.41)$$

where $f_{\beta oe}(E_i)$, $f_{\beta eo}(O_i)$ are corresponding regression models for ore production based on power consumption and/or corresponding power consumption based on the ore production volume.

Therefore, to solve the optimization problem by using the target function of type (2.39) and find appropriate vectors (2.40), it is necessary to apply certain optimization methods. Given the considerable number of unknowns (24), the exact solution to the task is quite difficult. Therefore, for an approximate solution, we apply a stochastic optimization approach. With this in mind, the corresponding algorithm for receiving the approximate solution to optimization problem (17) contains the following stages:

1. Starting the algorithm.

2. Setting initial data:

- the maximum number of iterations for the optimization algorithm (N_Σ);

- the maximum hourly power consumption ($E_i^{\max}$) for the random value generator;

- the minimum hourly power consumption ($E_i^{\min}$) for the random value generator;

- the admissible (recommended or optimal) daily power consumption

($E_\Sigma^{permissible\ value}$);

- the variable factor for the penalty function (r).

3. Initiating input values for the algorithm data:

- the suboptimal value of the target function ($I = +\infty$);

- the suboptimal value for specific hourly power consumption

($\frac{E_i^*}{O_i^*} = 0$);

- the number of the current iteration of the algorithm (j=1).

4. Generating 24 random values of daily time-of-day power consumption

($E_i, [i = 1 \div 24]$) with the regular distribution law $\xi_i = RND(0 \div 1)$ on the interval $[0 \div 1]$ and 'expand' it onto the required interval $[E_i^{\min} \div E_i^{\max}]$:

$$E_i = E_i^{\min} + \left(E_i^{\max} - E_i^{\min}\right)\xi_i \text{, i.e.}$$

$$\begin{cases} E_1 = E_1^{\min} + \left(E_1^{\max} - E_1^{\min}\right)\xi_1 \\ E_2 = E_2^{\min} + \left(E_2^{\max} - E_2^{\min}\right)\xi_2 \\ \dots \\ E_{24} = E_{24}^{\min} + \left(E_{24}^{\max} - E_{24}^{\min}\right)\xi_{24} \end{cases}$$

5. Calculating the corresponding 24 values of ore production ($O_i, [i = 1 \div 24]$) by relevant regression models [1] and (2.51)

$$\begin{cases} O_1 = f_{\beta oe}(E_1) \\ O_2 = f_{\beta oe}(E_2) \\ \dots \\ O_{24} = f_{\beta oe}(E_{24}) \end{cases}$$

6. Determining required averaged ($\bar{T}, \bar{P}$) and total (E_Σ) values for further calculations of the current target function (2.49)

$$\bar{T} = \frac{1}{24}\sum_{i=1}^{24} T_i,$$

$$\bar{O} = \frac{1}{24}\sum_{i=1}^{24} O_i,$$

$$E_\Sigma = \sum_{i=1}^{24} E_i.$$

7. Calculating the new current value of the target function (I) through (2.49).

8. If $I < I^*$, we redetermine the suboptimal value of the target function $I^* = I$ and corresponding vectors of power consumption and ore production:

$$E_i^* = E_i, O_i^* = O_i, i = 1 \div 24.$$

9. Adding the number of the next iteration j=j+1, if $j \le N_\Sigma$, proceeding to the next cycle (iteration) starting with block 4. Otherwise, it indicates achievement of the last optimization iteration. Proceeding to the final block of the algorithm.

10. Printing or adding to the database suboptimal values of the target function, vectors of power consumption and ore production – $I^*, E_i^*, O_i^*, i = 1 \div 24$.

11. Finalizing the optimization algorithm.

Fig. 2.31–2.35 show the optimization results of using the above algorithm. This is dynamics of changing the values of the target function (I, I^*), specific power consumption (E_i^*/O_i^*) and the penalty function ($f^{penalty}(\cdot)$) depending on the iteration number (the calculation step j).

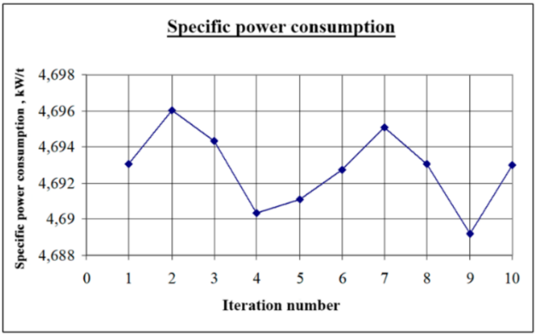


Fig. 2.31 – Change of the averaged value of specific hourly power consumption during optimization

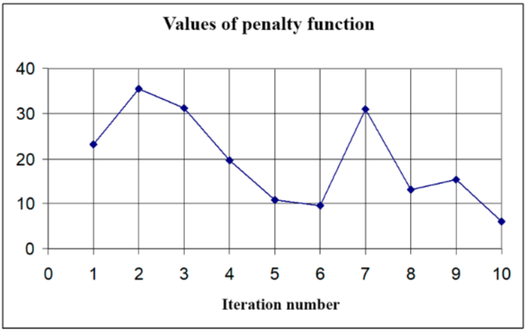


Fig. 2.32 – Change of the function of the penalty for excessive or insufficient power consumption

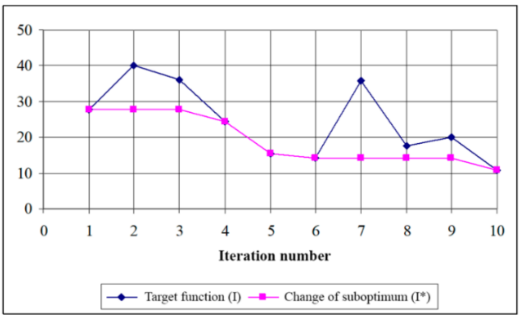


Fig. 2.33 – Change of the target function values (I) and the corresponding suboptimum (I*)

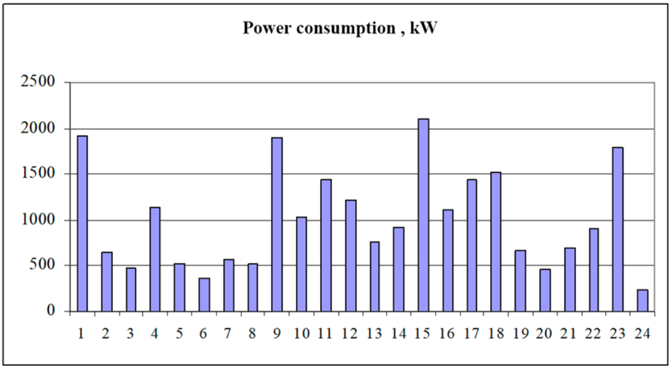


Fig. 2.34 – Vector value of hourly (daily) power consumption (E*) that corresponds to the suboptimum of the target function (I*) on the example of the Oktiabrska underground mine statistics

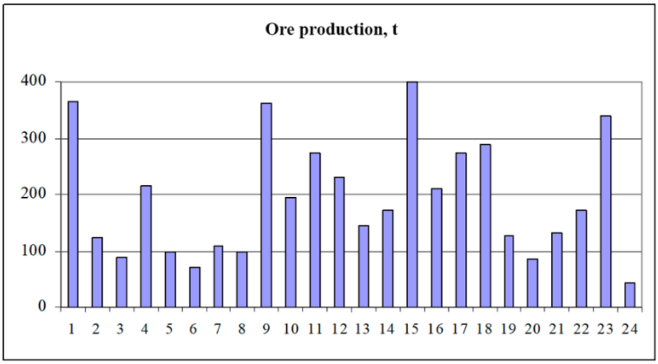


Fig. 2.35 – Vector value of hourly (daily) ore production (P*) that corresponds to the suboptimum of the target function (I*) on the example of the Oktiabrska underground mine statistics

Analysis of stochastic optimization (Fig. 2.33-2.35) results indicates that even with a rather small number of iterations N_{Σ}=10, it is possible to improve the initial solution by over 60% (the primary value of the target function *I**=27.7 and the final value on the last iteration *I**=10.7). Besides, the modelling enables determining vectors for daily time-of-day ore production (*O**) and corresponding power consumption (*E**) which corresponds to the suboptimal value of the target function (*I**). The obtained results can be used for recommendations on more efficient planning of the enterprise's operation.

To obtain a better solution, it is necessary to increase the number of iterations by 2-3 orders by forecast assessment of power consumption in a cost-based version.

2.6 Software and technical implementation of the ACS

Applying the approach proposed in [145, 147], the multichannel process of controlling power consumption of an iron ore underground mine can be provided in the form of a three-level hierarchical system. The adapted structure of the multichannel ACS based on a systematic combination of fuzzy control and optimization approaches is shown in Fig. 2.36. The proposed scheme demonstrates the hierarchy of individual subsystems and basic system connections as part of the multichannel *ACS of electric power consumption*.

Fig. 2.36 contains the following symbols: $OS_{ij} \in \Re$ is the *j-th* control channel of the *i-th* technological process (i.e. ore production, drainage, ventilation, etc.); $i=1,\ldots,N_s$; N_s is the number of technological processes; $j=1,\ldots,k_i$; k_i is the number of control channels of the *i-th* technological process; FC_{ij} is a fuzzy controller of OS_{ij}; $V_{ij} \in \Re$ is a vector of disturbing actions for OS_{ij}; $Y_{ij} \in \Re$ is a vector of input characteristics of OS_{ij}; $U_{ij} \in \Re$ is a vector of controlling actions of OS_{ij}; X_{ij} is a vector of data parameters on the state of OS_{ij}; $Y^{з}_{ij} \in \Re$ is a vector of tasks (insertions) of OS_{ij}; TP^{*}_{i} is a set of all local technological processes; $V^{*}_{i} \in \Re$ is a vector of basic disturbing actions of TP^{*}_{i}; $Y^{*}_{i} \in \Re$ is a vector of input characteristics of TP^{*}_{i}; X^{*}_{i} is a vector of data parameters on the current state of the set TP^{*}_{i}; $Y^{*з}_{i} \in \Re$ is a vector of tasks (insertions) for input characteristics of TP^{*}_{i}; FMM^{*}_{i} is a forecast mathematical model (regressor) for the *i-th* technological process.

There are three main levels of control: 1) by local mode parameters (ore production, drainage, ventilation, etc.); 2) by power consumption indices and costs; 3) by technological processes of a mine as a whole. Thus, for power consumption of ore production ($i=1$, $k_1=2$) the first channel (OS_{11}) is ore tonnage and haulage; the second channel (OS_{12}) is the drainage volume; V_{11}={ventilation volume}; V_{12}={ air intake volume}; Y_{11}, Y_{12}={power consumption, power costs}; U_{11}={ore volume}; U_{12}={mine water volume}; X_{11}={current power tariff}; X_{12}={mine mode indices}.

Other technological processes are formalized in a similar way, e.g. grinding, skip lift, etc. The resulting characteristics for technological processes (of the entire mine) are generally formed as follows: $V^*_1=V_{11}\cup V_{12}$ ($\cup$ is an the operation of logic combining); Y^*_1={power consumption, power costs}; $X^*_1=X_{11}\cup X_{12}$.

The upper level of the system in the power consumption optimization block analyzes the current state of the control object. Coordinated analysis of indices (technological and power consumption) is to determine the settings (tasks) for control systems of corresponding processes (at the middle level). Unlike existing approaches, decision-making (determining the necessary settings) in the system (Fig. 2.30) can be carried out by either maximizing production (minimax control) or improving through appropriate settings of type (2.10) - (2.17) or (2.37) – (2.41). The mathematical models for this are given above.

At the middle level, control (recommendations) is/are developed for the complex of technological processes of an iron ore underground mine. To do this, values of minimax or optimal top-level settings are used and tasks (settings) for controllers of all local processes and their corresponding control channels.

On the other hand, middle-level systems collect primary information from the subsystems of the lower level about the state of each channel (control actions, output, disturbance), carry out its primary processing, forecast input and output indices and use forecast regressors (PR^*i). The data are also transferred to the upper level for decision-making and determining optimal settings in order to coordinate power consumption control of individual technological processes and the mining complex as a whole.

The lower level of the system controls individual local technological processes of an underground mine. To do this, the level contains a certain number of control channels, and individual local processes can be controlled by several channels. Each channel has its own fuzzy controller functioning by means of algorithms (Fig. 2.3, 2.4). The task of the controller is to maintain the required setting value which is defined at the upper level of the system and obtained from the corresponding control subsystem of a specific (i.e. average) level. In turn, the subsystem of the lower level transmits information about the state of each channel (indices of control actions, values of information signals, disturbances, etc.) first to the mid-level system and further to the upper level.

Application of this approach ensures reliable determination of efficient values of current parameters of tasks (in the form of appropriate settings), stable work under distubances in basic control channels, as well as in case of constraints of type (2.38).

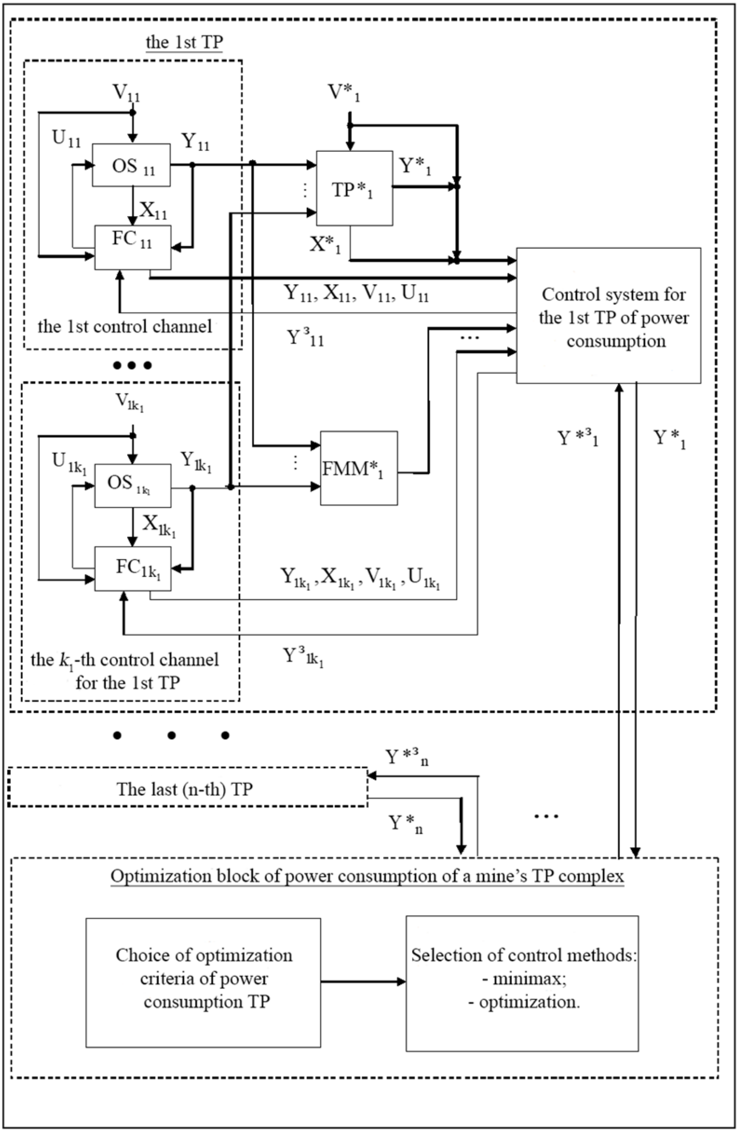


Fig. 2.36 – Structural diagram of the multichannel fuzzy control ACS of mining power consumption processes

The generalized functional diagram of implementing *the ACS of electric power consumption* is shown in Fig. 2.37. The first two levels are physically located on the industrial server of the system. Clients' workplaces use appropriate software directly from the application server. Information exchange is carried out from a local network (Industrial Gigabit Ethernet).

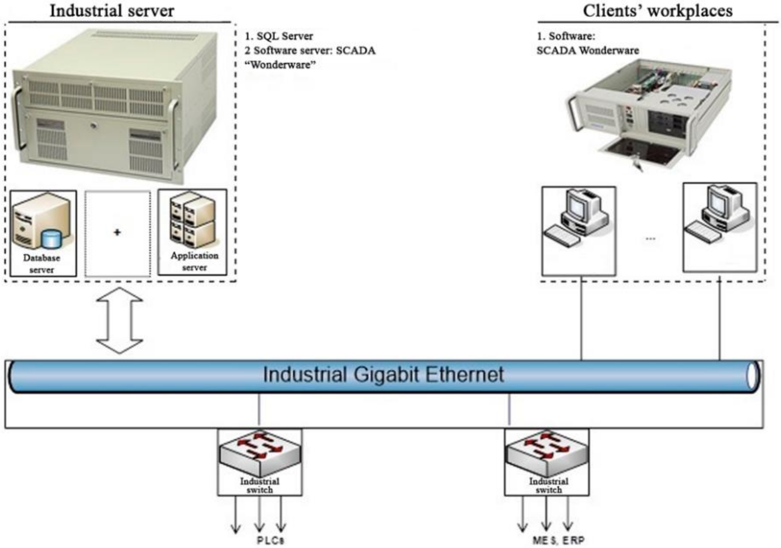


Fig. 2.37 – Simplified functional diagram of software-technical implementation of the ACS of electric power consumption

To control the lower level of the system (sensors, primary converters, executive devices), an industrial-level network is used. It combines an industrial server with a number of controllers (PLC), which in turn control the equipment of local technological processes. Similarly, integration of industrial subsystems of the middle level (MES type) is carried out. Interaction with the subsystems of the upper level of production management (ERP) is executed by using the corporate information network of an enterprise, while an industrial server is used as a gateway.

The software kernel is located on an industrial server. The smart component of the system has a set of typical fuzzy structures, which are assembled in the form of separate dynamic libraries (SCADA and/or integrated directly by PLC). Such libraries are freely connected to the ACS programme project by applying the corresponding APE functions. Embedded development tools or universal standard languages of C/C++/C# type and others are used as binding technologies. Integration of software developments as part of the ACS (including interface, SQL database queries, visualization and control functions) are implemented by Wonderware (SCADA) [147].

2.7 Methodological recommendations for implementing the ACS of electric power consumption at mining enterprises

In view of the search results set forth in the previous sections of this scientific study, we can state that structurally *the ACS of electric power consumption* is essentially the dominant component for the conditions of underground mining enterprises [146, 147].

Meanwhile, the basic goal of control is to monitor the levels of electric power flows during the day, which is understood as effective control according to efficiency and reliability criteria set by electricity consumers. This approach certainly encourages enterprises to solve other problems to improve energy efficiency of iron ore production. Of course, the maximum positive effect can be achieved through integrating all the directions mentioned.

Besides, as noted in the above sections of this study, along with validity of theory provisions, the need to develop practical realistic recommendations and a "road map" for transferring research results to practice of operating iron ore underground enterprises is one of the two system-forming components of solving the strategic problem of improving energy efficiency of iron ore production in Ukraine.

The formalization approach to selecting the structure of the subsystem of *the ACS of electric power consumption* as a component of *the ACS of electric power consumption* indicates that it should be based on the following principles.

Tactics of developing *the ACS of electric power consumption* of an industrial enterprise, including the mining one, can be formed in several ways. The first is the most effective, yet the most expensive one. It involves development of the ACS as a structure of a general design complex of an enterprise itself followed up by its implementation at the beginning of putting into operation the entire industrial complex. Unfortunately, this option is unlikely in current economic conditions of the national mining industry, since designing new mining enterprises is impossible at present.

The second option is gradual structuring of the ACS components. That involves synthesizing the structure of the ACS from individual structures, which will be components of a general synthesized system in the future. This approach compared to the first one is less effective, as it takes more time to complete, this certainly not contributing to a positive effect. However, there is such practice with sufficient chance of being realized at modern industrial enterprises.

The third option of creating the ACS of electric power consumption is the most efficient in current conditions of operating enterprises. It consists in the following.

For almost two decades, most mining enterprises of Ukraine have been using automated systems for power consumption control (ASPCCs). Yet, performance of control functions of these systems at individual enterprises varies. Meanwhile, it is the ASPCC that should become the basis for creating *the ACS of electric power consumption* by building up its other subsystems around the “base”. At the same time, from economical viewpoints it is essential to realize the system by using mass-produced technical tools.

Creation of *the ACS of electric power consumption* at Ukrainian mining enterprises is now very expensive and far from being quickly realized technically. Besides, as noted above, prices for iron ore materials in recent decades have been "falling", while profits of domestic iron ore mining enterprises are gradually decreasing to critical levels.

One of the most significant problems of implementing *the ACS of electric power consumption* with high functionality to be applied to national mining enterprises is its high cost determined by expensive electric machines. A more realizable option can be implemented at enterprises with installed ASPCCs, yet of a lower level and with clearly insufficient functionality but still ensuring control over power consumption as well as dispatching control.

This option enables a conclusion about a possibility to improve not only the equipment installed, but, which is more important, costs for project implementation.

In other words, at present, most, if not all, industrial enterprises have already implemented a number of preventive solutions, which form the basis for creating *the ACS of electric power consumption*.

Continuing the above analysis, we note that at Ukrainian mining enterprises, there is a great variety of automated systems for controlling and metering power consumption. The system implemenated at the PJSC "KZRK", which combines five underground mines and an open pit, is the most successful and simalteneously promising option in terms of transforming the ASPCC into *the ACS of electric power consumption*.

This system was initially created as a basis for further development of *the ACS of electric power consumption*.

In 1997, with the ideological and consultative participation of scientists supervised by Doctor of Engineering, Prof. Sinchuk, the PJSC "KZRK" introduced an automated commercial system of electricity metering as the first stage of implementing *the ACS of electric power consumption* (Fig. 2.38). It was in this tactical option that this automated complex was implemented into practice of both individual underground mines and the integrated works (association of underground mines) as a whole.

Fig. 2.39 examplifies designed and actual power consumption of Kryvyi Rih underground mines after the experimental use of *the ACS of electric power consumption*. As can be seen, the difference in values does not exceed 3%.

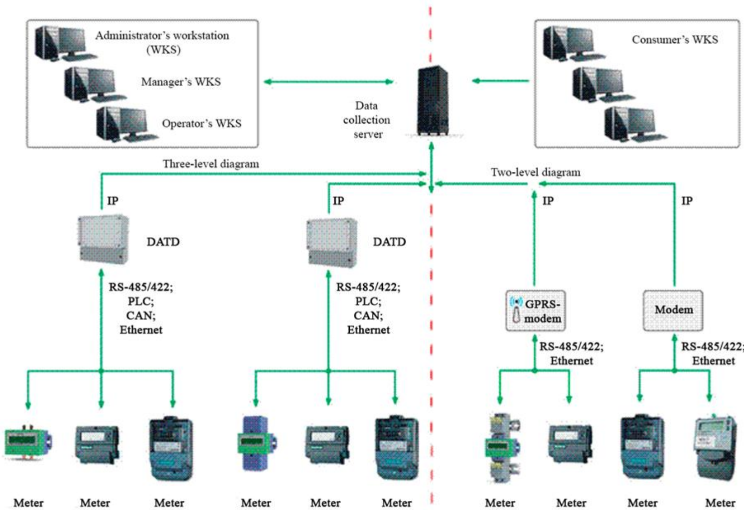
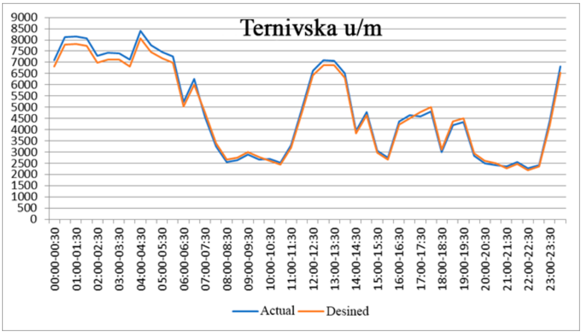


Fig. 2.38 –Simplified structure of the automated system of power metering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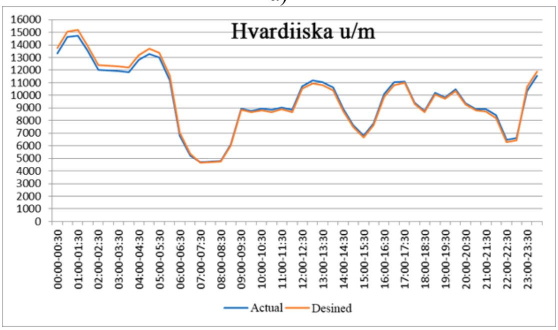
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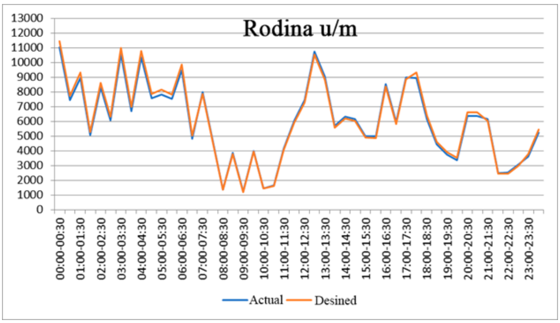
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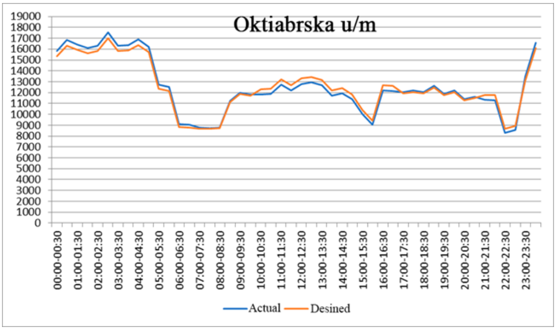

d)

Fig. 2.39 – Designed and actual power consumption at underground mines of Kryvyi Rih iron ore basin after experimental introduction of the ACS of electric power consumption according to power services of:
a) Ternivska u/m; b) Hvardiiska u/m; c) Rodina u/m; d) Oktiabrska u/m

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