Synthetic Ecological Engineering

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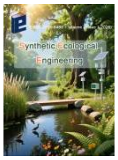

Research Article

Methodological Implementation of Biogenic Principles in Mining Technology

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KEYWORDS

subsoil development
nature-technical systems
technological paradigm
bio-inspired mining
biogenic principle
convergent technologies
proactive framework structures

ABSTRACT

The fundamental contradiction between the biological essence of humans and the abiological means of extracting solar energy to create food and habitat is a defining factor of their existence, shaping the modern image of our technocratic civilization. Traditional underground mining is largely extensive, focusing on mitigating the effects of rock pressure rather than addressing its root causes, leading to geotechnical instability. This study substantiates a new bioinspired convergent technology within the framework of a natural engineering system (NES) for resource development. The proposed approach implements the principle of prevention—the first of the five core bioinspired principles—drawing a functional analogy to the irreversibility of biological evolution. The technology is based on the improved construction of artificial load-bearing framework structures in the lithosphere. These structures preemptively compensate for rock pressure during extraction, ensuring the structural integrity of the geosphere. This option of merging biological and technical knowledge offers a (transformative) perspective – a ″green″ paradigm for the sustainable development of the global mineral resource complex.

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1. Introduction

During the course of evolutionary development, constant population growth, and the struggle for existence, humans were unable to occupy their natural biological niche. They used their intelligence to create an entirely different one, radically altering the way they extract solar energy. They learned to obtain this energy by destroying the equilibrium biological systems of the primary biota, replacing them with artificially balanced ecosystems for economic purposes, in which local equilibrium, in space and time, is maintained exclusively by human labor[1].

The implementation of these life-sustaining activities required the creation of a vast agricultural and industrial infrastructure, as well as a transportation network, covering the entire globe. Currently, more than 10% of the land surface is cultivated, and approximately 30% is used for other agricultural purposes. The share of urbanized land has increased more than fivefold over the past 200 years, reaching 3.8% of the total land area in 2000. There are forecasts for this share to increase to 20% by 2070 year [2]. Over the past two centuries, the most striking feature of the economic system has been the enormous quantitative and qualitative growth of all its components. The population has grown at rates far exceeding anything previously known in history. Over the past 100 years, the Earth's population has grown from 1.6 billion to 7.2 billion. The first doubling of the population occurred in 65 years, and the second in 38 years. Such an increase became possible only with an even greater expansion of energy and material wealth, the bulk of which is provided by the development of the mineral resource complex (Figure 1).

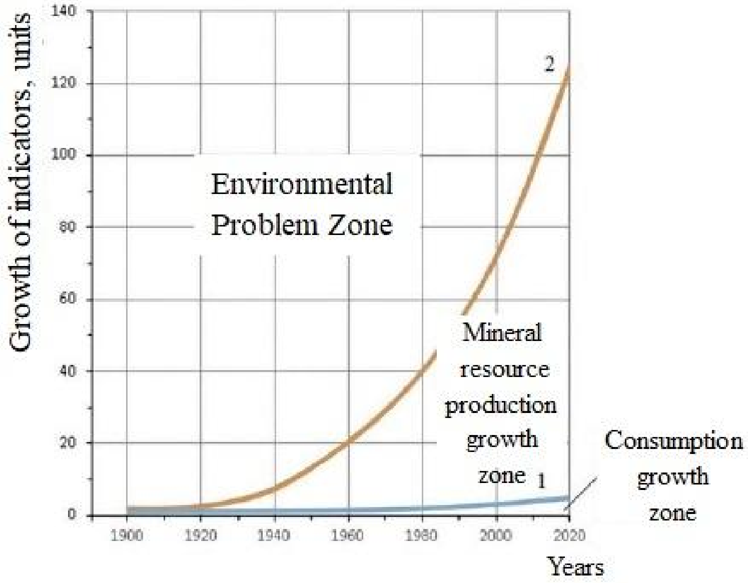

Figure 1. Indicators of the Growth of the Earth's Population (1) and the Volume of Lithosphere Extraction (2).

That's why, over the same period, the extraction of lithospheric material per person increased from 1.4 to 9.2 tons/year. Due to geological reasons, the extraction of minerals of economic value has always been accompanied by the inevitable extraction of waste rock in quantities significantly exceeding the volume of the mineral (Figure 2). Therefore, the total extraction of lithospheric material during the period under review increased from 34.2 to 151.2 tons/person/year [3-5].

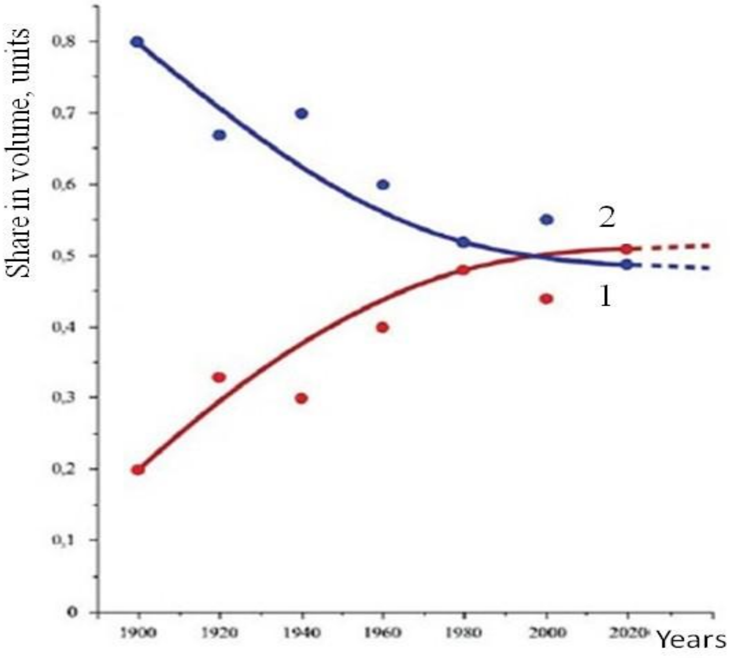

Figure 2. Qualitative structure of the total volume of extracted lithospheric matter:1 - share of minerals, units; 2 - share of solid waste, units.

The total mass of matter extracted from the lithosphere and incorporated in one form or another into circulation on the Earth's surface already accounts for nearly 85% of the global dry weight of biomass in all continental ecosystems, or 31% of the live weight of all animals and plants inhabiting the planet's landmass. Given these ratios, it is entirely possible to say that continued development of the mineral resource complex within the current technological paradigm poses a very real threat of unbalancing the entire system of matter circulation in the planet's biosphere.

The current stage of development of the mineral resource complex, as the material and energy foundation of the established technocratic civilization, is characterized by the fact that, along with standard requirements for the safety and economic efficiency of the technologies used, expectations and constraints associated with the implementation of the concept of sustainable development and the environmental imperative are becoming crucial.

The acceleration of technological progress, combined with the challenges of globalization, is constantly increasing the interconnectedness between society and technology [6]. In the current general technological paradigm for the development of the anthroposphere, issues of protecting and restoring natural biota are addressed as an afterthought, after profit has been generated. The technologies employed are built on highly specialized knowledge and are selected solely based on technical and economic criteria. This approach allows for the resolution of individual environmental issues through the implementation of additional, nature-like operations, but does not address the full range of problems associated with biological diversity and the structural features of the natural objects being protected.

Therefore, in methodological terms, environmental safety requirements should not be imposed on individual operations or processes, but rather should be embedded within a promising general technological paradigm so that environmental conservation becomes an integral feature of the technologies being developed and applied. The prevalence of man-made forms of environmental protection has increased dramatically. At the same time, the need has arisen to develop and implement a global concept for ensuring environmental safety in the development of the mineral resource complex as a whole, based on the greening of the technological paradigm in the field of integrated development of subsoil mineral resources.

2. Methodological Approaches

A review of scientific literature over the past decade and a half has revealed that a new field has emerged linking the concept of nature-based technologies (biomimetic technologies) with sustainable subsoil use. The primary focus of research has shifted from simply minimizing environmental harm to creating systems that mimic natural processes within the organizational structure of individual mining technologies.

Swarm robotic systems (swarmrobotics), which mimic insect behavior for autonomous mining in hard-to-reach areas (Off World project, Ma'aden), are actively developing. Nature-Inspired Algorithms (NIA) are being used to optimize mining planning and logistics, reducing energy consumption and the footprint of anthropogenic impacts.

Nature-based Solutions (NBS) are being implemented—solutions based on the use of natural processes for mine water treatment (phytofiltration) and for waste stabilization through the imitation of natural landscapes. In the field of primary processing of extracted raw materials, the transition to bioleaching is dominating as an environmentally friendly alternative to chemical methods, particularly for extracting critical metals (Li, Co) from low-grade ores and waste heaps. Research is increasingly being conducted to create digital twins of deposits that simulate the interaction of man-made systems with the biosphere as a single living organism.

A review article[7] proposes a unified concept combining three approaches:

(1) Nature-inspired algorithms (NIAs)—adapting the behavioral algorithms of living organisms (ant colonies, bee swarms, wolf packs) to optimize transport routes, mine planning, and energy-efficient drilling.
(2) Swarm robotics—the use of multiple autonomous agents interacting based on the principles of collective intelligence to improve safety (danger zone detection) and operational efficiency.
(3) Biomimicry in engineering—borrowing structural solutions from living nature to create new mining equipment.

The review [8] systematizes research from the past five years in areas such as biopolymers, biocolmatation, biocementation, and the use of plants and fungi for revitalization and slope stabilization. It emphasizes the transition to hybrid bioengineering solutions and notes the lack of standardized design principles, which hinders the industrial application of research results.

Additionally, in the article [9], the authors provide a classification of swarm algorithms (ASO, PSO, ABC, GWO, etc.) applicable to the stages of mining production—from exploration to transportation.

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Summarizing these studies, two main areas of exploratory research can be formulated:

1. Convergence of approaches: a shift is observed from the use of individual nature-inspired algorithms to the creation of integrated systems, where machine learning (NIAs) controls swarm robots, and biotechnology ensures the sustainability of geotechnical solutions. 2. Priority for Biomineralization: Microbial-induced carbonate precipitation (MICP) and the use of biopolymers are recognized as the most promising for stabilizing

waste heaps, controlling erosion, and reducing dust generation, although their practical application remains a technological challenge.

Furthermore, most research on nature-like technologies is in the laboratory and field testing stages (TRL 4-7). Standardization and interdisciplinary investment are needed to move toward industrial implementation. An assessment of the development prospects of this scientific field has shown that the principles of nature-like technologies extend beyond traditional mining, encompassing reclamation (agrovoltaics), space exploration (bioliching), and adaptation to climate change (thermosiphons for permafrost protection [7-9].

Considering the presented information as a whole, it is necessary, first of all, to note the enormous positive and promising significance of the emerging trend of nature-like technologies in mining. This alternative to the frequently used and rather vague term "green mining" implies the urgent need and timeliness of a technological revolution in the interests of ecology. At the same time, it should be noted that the level of formulation and solution of specific problems does not yet correspond to the real scale of the problem facing us all: the development of a global environmental crisis.

In this regard, the search for differentiated methodological approaches and methods for solving environmental problems based on the creation of technologies that ensure the production of all types of products necessary for humankind within the constraints determined by the conditions for preserving the Earth's natural biota is of paramount importance.

The changes in public consciousness that have occurred in recent years inevitably lead to a "greening" of thinking in all spheres of human activity. The most obvious reflection of this is the ever-growing understanding of the imperative need to transition to the application of "nature-like technologies," which are associated with the main hopes and promising paths to overcoming the global environmental crisis generated by the rapid development of the "Society of Unlimited Consumption," governed exclusively by economic criteria. It follows, therefore, that methodologically, technological answers to environmental challenges should be sought in the study of systems where these answers have already been obtained—that is, in biological systems. Therefore, the phrase "nature-like technologies," often used today, should be interpreted not as a set of some unusual technologies, but as a definition of the vector for applying research efforts, and as an indication that we intend to find new ways to purposefully transform technologies based on knowledge of living nature.

In this context, it is easy to identify the main types and kinds of nature-like technologies, presented in the classification in Figure 3.

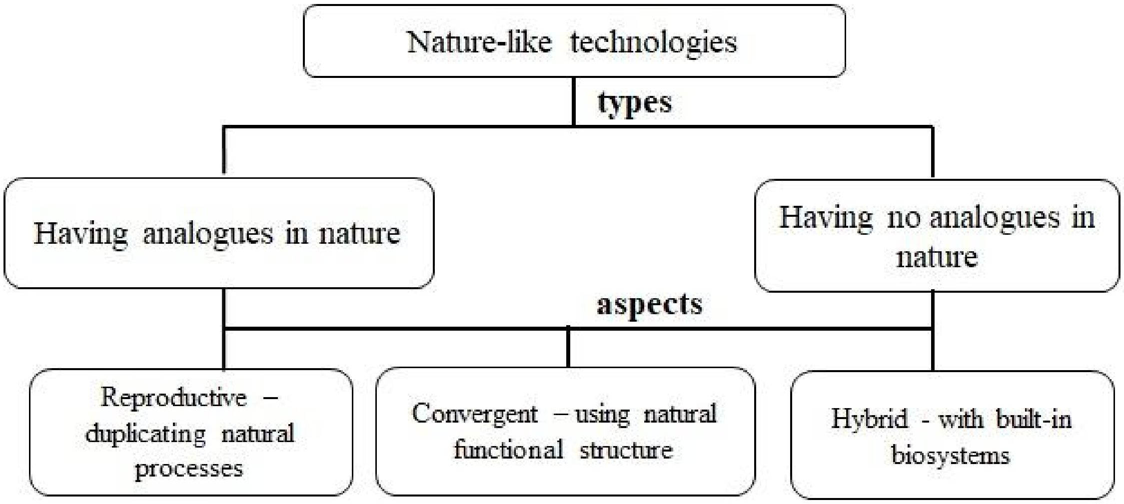

Figure 3. Classification of the concept of nature-like technology.

The figure shows that, depending on the degree of coincidence between the objective function of technological and biological systems development, the methodology for finding a nature-like solution boils down to either the effective duplication of certain processes occurring in biospheric objects in the technosphere (reproducing processes), or the creation of technical systems in which technological processes interact within a biospheric functional structure (convergent technologies), or the integration of a closed biological system into the anthropogenic functional structure of technology, performing actions and processes inherent only to biological systems that are inaccessible at the current level of knowledge (hybrid technologies) [10].

Since there are no natural analogues to the basic technological processes of solid mineral extraction (drilling rock, their explosive and mechanical crushing, the release and loading of rock mass, etc.), the creation of nature-like technologies for the development of such deposits can only be achieved through convergent technologies.

Methodologically, this corresponds to the transition from the analysis of the principles of functioning of equilibrium biological systems to the synthesis of the functional structure of a complex natural-technical system for the development of a deposit, the environmental consequences of which will be balanced by the tolerance of the area ofnatural biota that perceives the technogenic impact, in full compliance with the limitations of the environmental imperative and sustainable development (Figure 4).

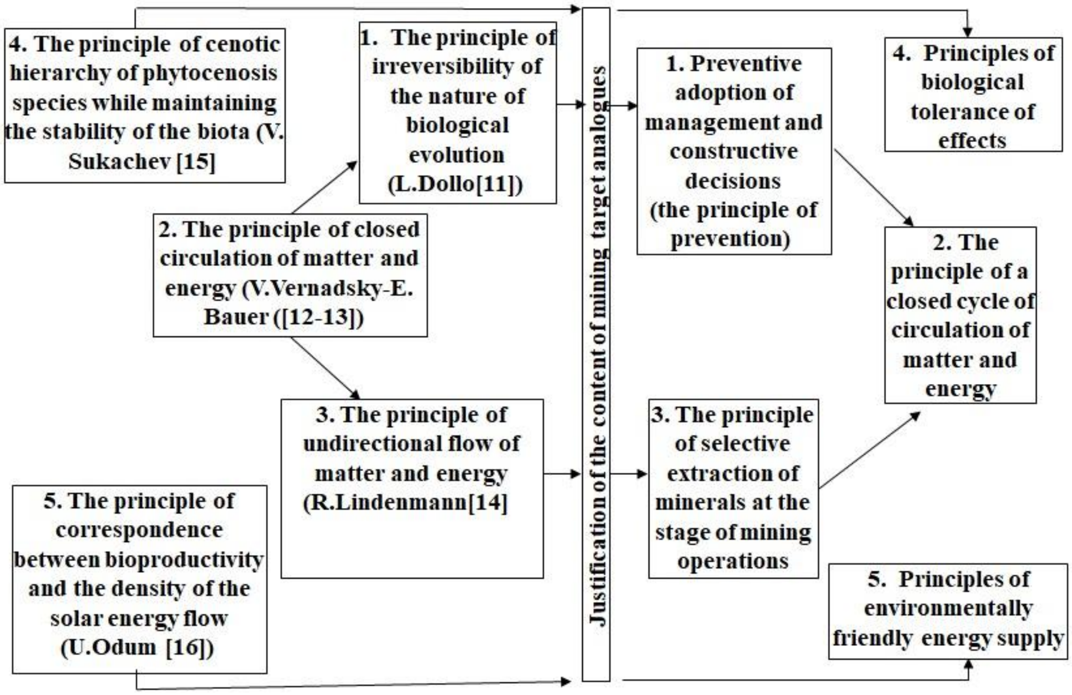

Figure 4. Biotechnological principles of formation of convergent mining technology [11-16].

Then, based on the well-known definition of a production cluster as a "mechanism for concentrating efforts," it can be argued that the main elements of the natural-technical system for developing deposit reserves are two full-fledged clusters, each of which "...concentrates efforts..." in different directions. One—the production-technical cluster—aims at the safe and efficient extraction of minerals, while the second—the environmental cluster—is formed as a system of actions and restrictions to prevent irreversible environmental consequences from the inevitable localized destruction of the lithosphere. Each of these clusters consists of several lower-order monoclusters, which, in turn, are formed from functional systems for various purposes (Figure 5). This transfer of the biogenic principles of functioning of environmentally friendly natural systems to the technosphere will ensure the creation of technical systems that limit external environmental impacts through the post-exploitation selfrestoration of phytocenoses of natural biota. Like any natural (in our case, nature-like) system consisting of simultaneously functioning elements, the structure of a production cluster reflects a hierarchy of biotechnical principles according to their degree of influence on the final result.

In the development of lithospheric mineral resources, the primary issue determining all parameters of the mineral extraction process is overburden pressure, an inevitable and constant consequence of the man-made destruction of the original rock masses. Therefore, the principle of preventive action, reflecting the need for a proactive solution to the problem of overburden pressure, clearly occupies a leading position in the aforementioned hierarchy of principles and should be considered first.

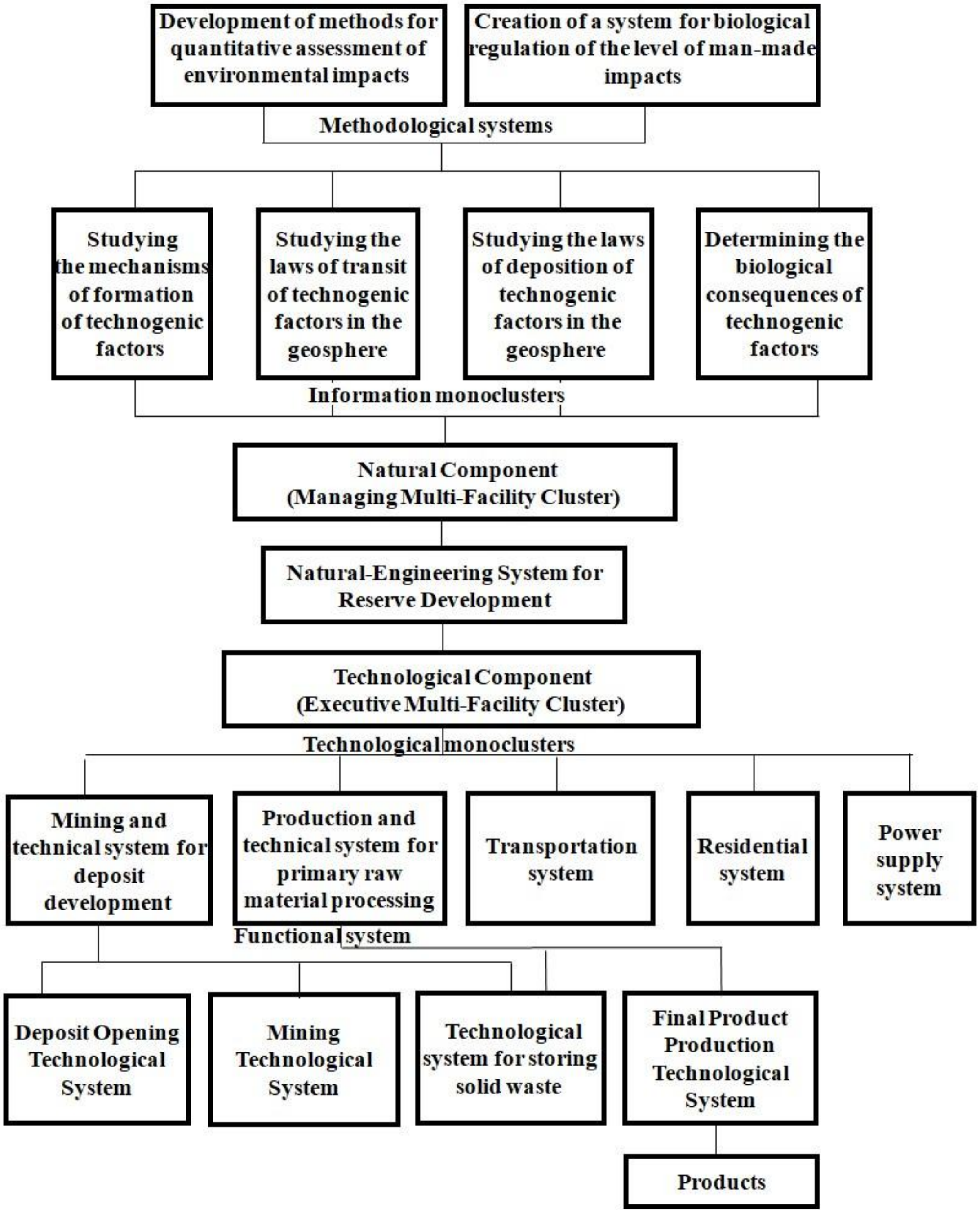

Figure 5. Functional structure of the production cluster of the natural-technical system for the development of deposit reserves.

3. Research Results

Based on the principle of preventive action, two main new directions for its application in the development of mining technologies can be identified. On the one hand, preventive technological decision-making forms the methodological basis of the existing design system for deposit development and, in this form, will exist in the context of convergent mining technologies. On the other hand, when applied to the problems of preserving natural biota, the use of this principle entails the mandatory proactive elimination of the causes of critical changes in the abiotic ecosystems when using mining technologies.

The general idea of such work can be defined as the integral unity of three local concepts reflecting the complex nature of the problem being solved.

The geophysical concept of developing a convergent mining technology consists of the proactive identification of the zone of man-made lithospheric destruction from the general field of initial rock mass stresses, by separating the processes of mineral extraction and overcoming rock pressure, through the early construction of a spatial system of artificial support structures within the boundaries of the mined lithospheric area.

Ensuring the feasibility of implementing this concept completely predetermines the order of mining operations, as well as the sequence and relative volumes of their application. It is quite obvious that the decisive construction of support structures is possible based on ore mining technologies with full hardening backfill of the mined space, with fairly stringent requirements for the quality of the backfill material. The methodology for determining the parameters of a "frame" structure in underground mining is quite simply formulated based on the well-developed theory of honeycomb structures used in other industries (Figure 6).

As shown in [17], a honeycomb core system in a three-layer structure maintains resistance to external loads as long as the ratio of the allowable compressive stress for the entire system, designated as the "reduced" filler (σ_z), and the critical stress for the main filler material (σ_{cr}) is directly proportional to the ratio of the elastic modules (E_z and E_{fact}) of these structural elements (Figure 6a).

$$\frac{\sigma_z}{\sigma_{cr}} = \frac{E_z}{E_{fact}}$$

If these ratios are observed, the critical stress in the sidewall of square honeycomb blocks (Figure 6b) is determined from the expression:

$$\sigma_{cr} = \frac{P \cdot S}{4 \cdot \delta_{fact} \cdot r_c} \cdot k_1 \cdot k_2$$

where P is the specified external specific load; S is the area of a single honeycomb element; k_1 and k_2 are empirical coefficients that take into account the shape of a single honeycomb element; and the ratio of the perimeter of the honeycomb element to its height.

From this, we can derive an expression for calculating the wall thickness of a honeycomb block (in our case, the thickness of the dividing artificial pillar erected during the first stage of development):

$$\delta_{fact} = \frac{P \cdot S}{4 \cdot \sigma_{cr} \cdot r_c} \cdot k_1 \cdot k_2$$

As numerous studies of the strength characteristics of honeycomb structures have shown, the optimal parameters of honeycomb core elements are determined not only by the properties of the material from which it is made, but also by the linear parameters of the core and the load-bearing layers of the structure.

Applying these principles to the proposed "framework" mining technology opens up real prospects for a radical solution to environmental problems in the development of ore deposits:

- the advance construction of a load-bearing "framework" structure ensures the preservation of the overlying rock mass and the earth's surface during subsequent extraction of the main reserves;
- fencing the mining area before it begins will maximize the preservation of all fluid-bearing horizons and protect mining operations from their impact;
- the formation of the mined-out space as a system of artificially contoured cavities creates conditions for the disposal of all types of industrial waste.

The dimensions of the horizontal section of each excavation unit are determined by the conditions of the technologies used for their development and filling.

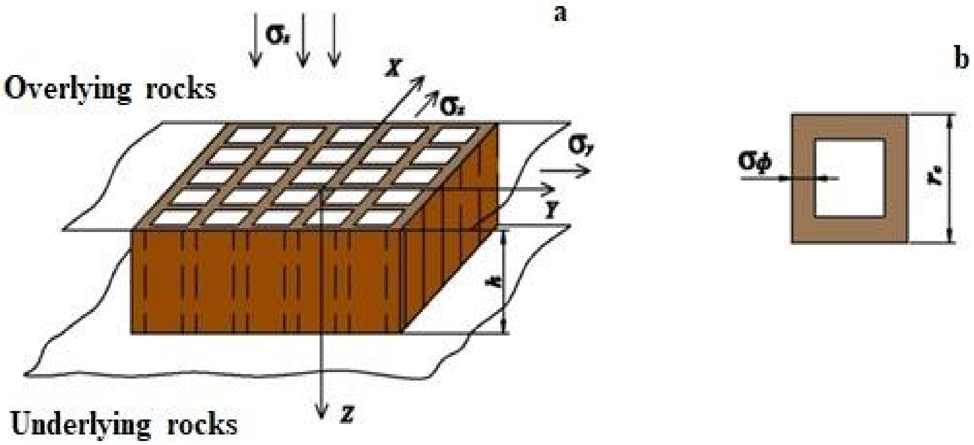

Figure 6. Structure of a honey comb structure for field development conditions: a – general view; b – elementary block being mined.

The overall correction factor k_0 is formed as the sum of local factors accounting for the shape of the honeycomb core cell (k_1) and the ratio of the cell's cross-sectional perimeter to its height (k_2). Both factors are determined empirically and vary within a fairly wide range. The former ranges from 1.54 to 3.0, while the latter ranges from 14.5 to 3.6 [18].

To implement this concept, development of the deposit (or part of it) should begin with dividing the deposit into minable areas with reserves equal to the enterprise's annual production by mining the marginal reserves of the area and constructing delineating artificial massifs—an upper and lateral massif (Figure 7).

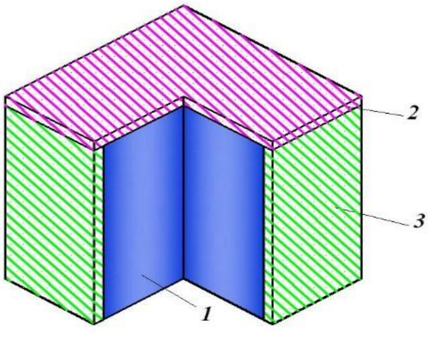

Figure 7. Formation of a protected zone (mined area) during the construction of delineating pillars: 1 – part of the ore body; 2 and 3 – respectively, the upper and lateral delineating artificial massifs.

The thickness of the lateral delineating massifs may be constant (in the case of simple contact between the ore body and the host rock or when constructing a massif within the ore) or variable toward the outer contour of the ore body (in the case of a complex contour). The shape of the mined area in horizontal cross-section may be arbitrary, depending on the actual morphology of the ore body being mined. Then, during the next stage of commissioning, the internal volume of the mined area is divided into extraction units by constructing a system of dividing artificial massifs (Figure 8).

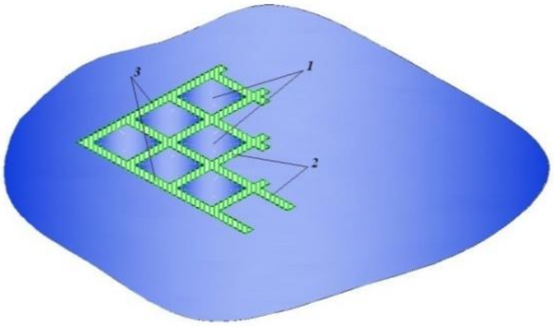

Figure 8. Scheme of the developed area after the construction of dividing artificial massifs: 1 - extraction units; 2 and 3 - respectively, dividing and delineating artificial massifs prospects and for a radical solution to environmental problems in the development of ore deposits.

Based on the biologically determined order of conducting mining operations, when the first structure erected ensures geomechanical unloading of the main volumes of the ore massif, which is essentially a framework within which large-scale cleaning operations are carried out, the proposed new direction can be called the development of a “framework” mining technology for underground mining of deposits, which is a deterministic system of technological clusters for various purposes, the interaction of which over time is regulated by biogenic principles.

Applying the outlined principles to the proposed "framework" mining technology opens up real prospects for a radical solution to environmental problems in the development of ore deposits:

- the advance construction of a supporting "framework" structure ensures the preservation of the overlying rock mass and the earth's surface during subsequent extraction of the main reserves;
- fencing off the mining area before it begins will maximize the preservation of all fluid-bearing horizons and protect mining operations from their impact;
- the formation of the mined-out space as a system of artificially contoured cavities creates conditions for the disposal of all types of industrial waste.

The dimensions of the horizontal cross-section of each excavation unit are determined by the conditions of the technologies used for their development and backfill.

To develop methods for determining the parameters of natural-technical systems for underground mining of solid mineral deposits, based on the general principles of using three-layer honeycomb structures, it is advisable to utilize the fundamental principles of modern homeostatics, as a new branch of cybernetics that studies the mechanisms of control and interaction of complex systems of various natures [19]. Since, regardless of the design of each element, the homeostatic control principle is the same for all types of complex systems, it forms functional fractals, the substantive elements of which are determined by the nature of the interacting systems. Therefore, information about the functioning of one system can be transferred to another through the step-by-step formation of a new homeostat based on the structure of an existing homeostat, with the replacement of its substantive elements with target analogues corresponding to the content of another system [20].

3.1. The Geotechnological Idea

Behind the proposed concept is that fundamentally new opportunities for improving safety and efficiency are achieved through the targeted arrangement of existing mining technologies with different characteristics in time and space.

The advanced creation of a spatial system of artificial massifs for various purposes enables the implementation of the fundamental principle of ensuring the environmental safety of natural-technical mining systems – the principle of isolating the zone of man-made destruction arising during the operation of the technical component of the system within the initial stress field in the host rock mass from rock pressure.

. It should be noted that the advanced construction of artificial massifs significantly increases the reliability of geological information about the mining conditions of each stope, as well as the ore quality and distribution of the valuable component. Further development of the deposit area involves sequential or parallel extraction of the delineated units using established geotechnologies.

The mining sequence is determined by the stability of the separating artificial massifs, such that the diagonals of two or more simultaneously mined stopes (in horizontal cross-section) always form a straight line along the stope front within the area being mined (Figure 9).

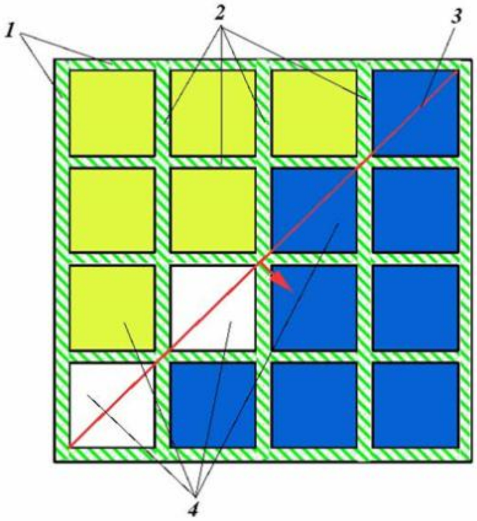

Figure 9. General order of development of extraction units: 1 and 2 – respectively, delineating and dividing artificial massifs; 3 – conditional line of movement of the working cut front; 4 – extraction units.

This enables the development of the majority of the deposit's reserves while being completely protected from the negative impact of virtually all geofactors arising from large-scale man-made disturbances to the equilibrium dynamic structures of the lithosphere. This also allows the selection of ore mining technology in each specific extraction unit to be tailored solely to its local mining characteristics.

The early formation of contact between the mined rock mass and the artificial rock masses creates favorable conditions for explosive rock fracture, with a corresponding increase in the quantitative and qualitative performance of mining operations. This completely eliminates the loss of unmined ore and external sources of ore dilution.

After the reserves of each extraction unit have been fully mined, artificially contoured stable cavities are formed, suitable for the storage of the majority of solid waste from the mining and processing operations, ensuring the implementation of a closed-loop circulation of mined lithospheric material. The division of the area being mined into extraction units, the spatial position of which, as well as the size and shape, are fixed during the creation of a system of artificial massifs for various purposes, makes it possible to implement the above-mentioned principles of constructing nature-like mining technologies for each extraction unit in strict accordance with the individual characteristics of its geological structure (Figure 10).

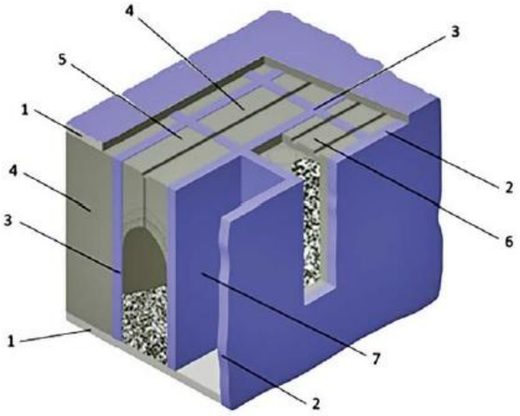

Figure 10. The principal of the schemeof the construction and application of a "framework" mining technology. Artificial massifs:1 - enclosing horizontal and 2 - vertical; 3 - separating; Mining blocks:4 - prepared, 5 - to mine by blasting- gravitational and 6 - blasting mechanical geotechnologies; 7 - Mined-out block.

The ratio of ore volumes extracted at each stage of mining a section of an ore body is determined by the stability conditions of the extraction block spans (l_b), their length (b_i), and the thickness of the vertical fencing and dividing artificial massifs (m_b). In general, the area of the section being mined (S_p), divided into N_i extraction blocks, is:

$$S_p = A \times B = \left(\sum_1^{N_a} l_b + \sum_1^{N_{a+1}} m_b\right)\left(\sum_1^{N_b} b_i + \sum_1^{N_{b+1}} m_b\right),$$

where: A and B are the width and length of the section being mined, respectively, in m.

Hence, we have:

$$N_i = \left(\frac{A - m_b}{l_b + m_b}\right) \cdot \left(\frac{B - m_b}{b_i + m_b}\right), pcs$$

The volume of balance reserves (V_{fr}) extracted during the frame structure construction stage will generally be:

$$V_{fr} = (S_p - \sum_1^{N_i} l_{b_i} \cdot b_i) \cdot H_{st}$$

where S_p- is the total ore area of the mined section, b_i is the length of the working block, and H_{st} is the height of the mined section.

The share of the frame structure (d_k) in the total production volume (in relative terms) will be:

$$d_k = \frac{V_k}{H_{st} \cdot S_p}$$

Accordingly, the share of working blocks (d_b) will be equal to:

$$d_b = 1 - d_к .$$

Thus, the application of the principles of hierarchical self-organization to structuring the technological processes of a mining cluster ensures an adaptive response to changing geological conditions.

The concept of this hypothesis was presented at the 21st World Mining Congress (Krakow). The results of the subsequent discussion confirmed the correctness of the chosen direction of scientific research [21].

At the stage of substantiating the technology for constructing "frame" structures, industrial experiments were conducted during the underground mining of the Yakovlevskoye iron ore deposit (Russia) [22]. The main options for mining minerals with hardening backfill during the construction of "frame" structures were tested. As a result, a methodology for selecting the composition of hardening mixtures used in various mining and geological conditions was substantiated.

A series of modeling studies was conducted to establish patterns of secondary stress field development, both during the construction of "frame" structures and during the mining of mining blocks.

A Great Bot D600 PRO industrial 3D printer and Fused Depsition Modeling (FDM) technology were used to generate models of the structural elements. The numerical models of the studied mining and engineering systems were adapted to the application conditions of MAP3D software and the Dips, RocData, Unwedge, and PicSure geomechanical programs.

Analysis of the obtained results showed that the implementation of the biogenic principle in the development of a "framework" version of convergent mining technology radically changes the nature of the development and structure of the secondary stress field. Of fundamental importance for the prospects for further development of the delineated reserves of the working area is the fact that this area is unloaded and geophysically isolated from the influence of the original stress field. Therefore, subsequent development of the reserves of the working blocks does not compromise the geophysical stability of the established mining and engineering system and enables the application of any technological solutions for both ore extraction and the final geophysical rehabilitation of the mined-out space.

3.2. The economic idea is that the above-substantiated volume of artificial arrays for various purposes (d_k) in the total volume of the allocated mining area can be determined from the expression:

$$d_k = \frac{V_{min} - V_{fr}}{V_b - V_{fr}}$$

where: V_{min} – the mining costs that ensure breakeven, rubles/t;

V_b and V_{fr} – the actual mining costs at the stage of mining the mining blocks and at the stage of constructing artificial massifs for various purposes, respectively, rubles/t.

It is these ratios between the specific ore volumes extracted by various technologies and the costs of these operations that determine the physical essence of the economic concept of the new approach, which is that the effectiveness of the proposed solutions is ensured by a functionally justified combination of high- and low-cost mining technologies, the ratio between which is determined by specific geomechanical conditions.

4. Conclusion

This paper develops a theoretical basis for a new scientific field—convergent mining technologies—that incorporates five key biotechnological principles of their operation. The proposed concept for implementing the first principle is based on the integration of geophysical, geotechnological, and economic aspects, enabling the implementation of a preventative approach to managing the state of the rock mass and the subsoil as a whole.

Using a confirmatory factor analysis of the functional structure of geotechnologies, it was demonstrated that for each morphological type of deposit, the form of implementation of this principle is determined by the maximum factor weight of the key processes in the technological cycle.

The synthesis of the identified patterns resulted in standard design solutions for developing large ore deposits, protected by patents [23-25]. This confirms not only the theoretical value but also the technical feasibility of the proposed methodology.

The potential for expanding the scope of application of the developed ideas (the practical significance of the work) is supported by the existing scientific groundwork for creating closed cycles for the circulation of lithospheric matter in technosphere production systems. In particular, methods for recycling fine-grained enrichment waste for permafrost areas have been proposed, as well as a patented hybrid carbon dioxide capture technology for coal-fired power plants [26,27]. The new technology, operating in a closed carbon cycle with the release of oxygen into the atmosphere, demonstrates the environmental effectiveness of this approach.

Author’s Contributions

Yu.P., G.V. conceptualization, methodology, formal analysis , writing original. Yu. P. validation, investigation. G.V. Yu. P Writing – Review. Authors have read and agreed to the published vertion of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest, and permission from other copyright holders is not required.

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