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ЕКОНОМІКА ТА МЕНЕДЖМЕНТ

1.FEJEZET.
GAZDÁLKODÁS ÉS MENEDZSMENT

CHAPTER 1.
ECONOMICS AND MANAGEMENT

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THE FRACTAL APPROACH AS A METHOD FOR STRATEGIC REGULATION OF THE EDUCATIONAL AND ECONOMIC ECOSYSTEM OF A DIGITAL UNIVERSITY

Abstract. *In the current conditions of digitalization, structural transformations of the global labor market, and increased requirements for the adaptability of educational systems, there is a need to revise traditional approaches to regulating the training processes within university education. The article is devoted to the substantiation of the fractal approach as an effective method of strategic management of the educational and economic ecosystem of a digital university. A scientific model is proposed that considers the recursive, self-similar, multilevel, and dynamic nature of the digital educational environment and allows for ensuring the adaptability of educational structures to the challenges of the digital economy. The methodological foundations for the transformation of university education in the digital age are revealed, in particular in terms of building integrated quality indicators based on normalized indicators and principal components. The necessity of using multidimensional data, indices, expert opinions, ratings, and time series to analyze and predict the efficiency of digital university subsystems is substantiated. Mathematical formalizations are proposed that allow for the evaluation of fractal structures of the educational system at different hierarchical levels and the derivation of generalized integral performance indicators. Particular attention is paid to the use of artificial intelligence technologies, precedent modeling, and knowledge-based approaches in management decision-making. The article proves that a digital university is not only an*

educational organization, but also a complex socio-technical fractal system capable of self-organization, self-development, and flexible functioning under conditions of uncertainty. It is noted that the fractal approach allows for aligning strategic development goals with tactical and operational management actions at different levels of management. The approaches to modeling the educational and economic ecosystem of a digital university proposed by the author open up new prospects for forecasting the development of intellectual capital, optimizing management processes, and ensuring the sustainability of the educational system in the digital environment.

Keywords: *digital university, fractal model, strategic regulation, educational and economic ecosystem, intellectual capital, digitalization.*

JEL Classification: E24, I20, I25, N3

Absztrakt. *A digitális korszak, a globális munkaerőpiac strukturális átalakulása és az oktatási rendszerekkel szembeni fokozott alkalmazkodási igények fényében felmerül a szükségesség, hogy felülvizsgáljuk a hagyományos megközelítéseket a munkaerőképzés szabályozásában az egyetemi oktatás keretében. A cikk a fraktális megközelítés tudományos megalapozottságát tárgyalja, mint hatékony módszert a digitális egyetem oktatási-gazdasági ökoszisztémájának stratégiai irányításában. A kutatás egy tudományos modellt javasol, amely figyelembe veszi a digitális oktatási környezet rekurzív, önhasonló, több szintű és dinamikus természetét, valamint lehetővé teszi az oktatási struktúrák alkalmazkodását a digitális gazdaság kihívásaihoz. Részletesen bemutatásra kerülnek a digitális korszakban zajló egyetemi oktatás átalakításának módszertani alapjai, különös figyelmet fordítva az integrált minőségmutatók kialakítására a normalizált mutatók és fő komponensek alapján. Indokolt a többdimenziós adatok, indexek, szakértői értékelések, rangsorok és időbeli sorozatok alkalmazása az oktatási rendszer digitális egyetemi alrendszereinek hatékonyságának elemzésére és előrejelzésére. A cikk matematikai formalizmusokat javasol, amelyek lehetővé teszik a fraktális struktúrák értékelését az oktatási rendszer különböző hierarchikus szintjein, valamint segítenek az integrált működési mutatók megfogalmazásában. Külön figyelmet kapnak a mesterséges intelligencia technológiák, a precedensmodellezés és a tudásalapú megközelítések alkalmazása a döntéshozatalban. A cikk arra a következtetésre jut, hogy a digitális egyetem nemcsak oktatási szervezet, hanem egy összetett szociális-technikai fraktális rendszer is, amely képes az önszerveződésre, az önfejlesztésre és a rugalmas működésre a bizonytalanság környezetében. Megállapítást nyert, hogy a fraktális megközelítés lehetővé teszi a fejlesztési stratégiai célok összehangolását a különböző szintű taktikai és operatív irányítási lépésekkel. A szerző által javasolt megközelítések az oktatási-gazdasági ökoszisztéma modellezésére a digitális egyetemen új perspektívákat nyitnak az intellektuális tőke fejlődésének előrejelzésében, az irányítási folyamatok optimalizálásában és az oktatási rendszer fenntarthatóságának biztosításában a digitális környezetben.*

Kulcsszavak: *digitális egyetem, fraktális modell, stratégiai szabályozás, oktatási-gazdasági ökoszisztéma, intellektuális tőke, digitalizáció.*

Анотація. *У сучасних умовах цифровізації, структурних трансформацій глобального ринку праці та підвищених вимог до адаптивності освітніх систем постає необхідність перегляду традиційних підходів до регулювання процесів підготовки кадрів у межах університетської освіти. Стаття присвячена обґрунтуванню фрактального підходу як ефективного методу стратегічного управління освітньо-економічною екосистемою цифрового університету. Запропоновано наукову модель, яка враховує рекурсивну, самоподібну, багаторівневу й динамічну природу цифрового освітнього середовища та дозволяє забезпечити адаптивність освітніх структур до викликів цифрової економіки. Розкрито методологічні засади трансформації університетської освіти в умовах цифрової епохи, зокрема в частині побудови інтегральних індикаторів якості на основі нормалізованих показників та головних компонент. Обґрунтовано необхідність використання багатовимірних даних, індексів, експертних оцінок, рейтингів і часових рядів для аналізу й прогнозування ефективності підсистем цифрового університету. Запропоновано математичні формалізації, які*

дозволяють здійснювати оцінювання фрактальних структур освітньої системи на різних ієрархічних рівнях та виводити узагальнені інтегральні показники діяльності. Особливу увагу приділено використанню технологій штучного інтелекту, прецедентного моделювання та знаннєвоорієнтованих підходів у прийнятті управлінських рішень. У статті доведено, що цифровий університет є не лише освітньою організацією, а й складною соціотехнічною фрактальною системою, яка здатна до самоорганізації, саморозвитку та гнучкого функціонування в умовах невизначеності. Зазначено, що фрактальний підхід дозволяє узгоджувати стратегічні цілі розвитку з тактичними й оперативними управлінськими діями на різних рівнях управління. Запропоновані автором підходи до моделювання освітньо-економічної екосистеми цифрового університету відкривають нові перспективи для прогнозування розвитку інтелектуального капіталу, оптимізації управлінських процесів і забезпечення сталості освітньої системи в цифровому середовищі.

Ключові слова: *цифровий університет, фрактальна модель, стратегічне регулювання, освітньо-економічна екосистема, інтелектуальний капітал, діджиталізація.*

Problem statement. The digital transformation of the higher education system in the context of global structural changes, growing geopolitical turbulence, and the dynamic evolution of the labor market necessitates a revision of traditional models of professional training and personnel potential management. The current system of higher education management is characterized by excessive centralization, inertia of management mechanisms, and fragmented implementation of innovations, which does not allow for the full sustainable development of digital universities as complex socio-economic systems. Educational institutions lose their ability to respond flexibly to changes in demand, technological challenges, and economic instability.

In these conditions, there is a need for new conceptual foundations for regulating the educational and economic ecosystem that operates in an open digital environment. Traditional linear approaches to analysis and decision-making do not meet modern requirements for the multilevel, dynamic, and self-organized nature of university structures. The fractal approach, based on the principles of self-similarity, nonlinearity, and multicomponent hierarchy, offers an innovative toolkit for modeling, forecasting, and strategic management of a digital university. In this regard, a scientific and practical problem arises: how to ensure holistic, adaptive, and effective regulation of training within the digital transformation of higher education using fractal methodology.

Literature review. The issues of digital transformation of the educational environment and the use of innovative services and information technologies in the training processes are actively covered in the modern scientific literature. Domestic researchers have made a significant contribution to the development of the concepts of university education digitalization, in particular P. Huk and O. Skliarenko, who substantiate the economic feasibility of modernizing enterprises using automated control systems and digital technologies in training specialists [1]. Digital tools to support innovative activity in the educational and entrepreneurial environment are considered in the works of Ya. Kolodinska, O. Skliarenko, and O. Nikolaievskyi, who

analyze the possibilities of using digital services in the development of business ideas [2].

Significant theoretical and methodological approaches to the digital transformation of the educational process are presented in the publications of O. Skliarenko, S. Yahodzinskyi, and A. Nevzorov, which consider digital interactive technologies as a key factor in an effective educational environment [3]. Modern pedagogical approaches to interactive teaching of higher education students are analyzed in the research of O. Khomenko, M. Paustovska, and I. Onyshchuk [4]. The socio-cultural aspects of the information space that influence the digitalization of higher education are comprehensively revealed in the monograph by S. Yahodzinskyi [5]. Such an interdisciplinary approach forms the basis for further substantiation of fractal modeling in the management of a digital university as a complex educational and economic system.

Identification of previously unresolved parts of the overall problem. Despite the active research on the digitalization of higher education, the issue of formalizing the structural features of a digital university as a hierarchical educational and economic system with self-similarity properties remains insufficiently covered. In particular, there are no clearly defined methodological approaches to modeling and managing such structures, considering their fractal nature, multi-level dynamics, and interaction of educational, managerial, and economic components.

Research aim and objectives. The aim of the research is to substantiate theoretically the feasibility of using the fractal approach for the strategic regulation of the educational and economic ecosystem of a digital university and to develop tools for assessing, forecasting, and adaptive management of intellectual capital formation processes based on fractal models and analytical indicators.

Results and discussions. The formation of a methodology for the transformation of the training system in the digital economy requires the creation of scientifically based tools for the strategic regulation of educational and economic processes within the new generation of universities. The high level of complexity of the system of continuing education and training requires a study that considers the multidimensionality, hierarchy, and heterogeneity of educational and economic data - quantitative, qualitative, and nominal. In such conditions, classical methods of statistical analysis based on the assumption of normal distribution of data and independence of observations are insufficient to adequately describe the functioning of digital university structures.

Educational data in a new generation university - a digital university - do not comply with normal distribution laws, they are fragmented, variable, and often dependent on each other [6, p.57]. The application of traditional methods of regression and factor analysis is complicated by the incompleteness and heterogeneity of educational information, the lack of stable parameters, and the unstable structure of variables. In this regard, there is a growing need to use alternative approaches to modeling, including regularized algorithms, principal component analysis, and non-standard mathematical concepts that can take into account system complexity, dynamic hierarchy, and self-organization.

Despite the active implementation of intelligent models, such as neural networks, fuzzy logic, and genetic algorithms, most of them do not consider such properties of educational and economic systems as structural self-similarity, fractal organization, multi-stage, and repeatability of management models [7;8]. In this context, fractal theory is a promising paradigm for the strategic regulation of the digital university as a complex educational and economic ecosystem. The fractal approach takes into account both horizontal and vertical repeatability of structures at different levels - from individual educational direction to state policy in the field of digital education.

Within the digital university, compliance with fractal characteristics can be clearly seen [1;3;6]. First, recursiveness, i.e., the presence of structural similarities, where educational functions and management approaches are repeated at the level of faculties, institutes, universities, educational clusters, and national systems. Second, structural complexity - digital universities operate in conditions of multidimensional data, digital interaction, hybrid formats, and variable composition of participants. Third, detail - as the educational system scales, more and more elements and connections are revealed that were not previously taken into account but affect the effectiveness.

In addition, the fractal dimension allows us to take into account non-standard, “incomplete” types of structures that characterize digital learning spaces. The property of sensitivity to initial conditions inherent in complex fractal structures reflects the dependence of learning outcomes on the initial educational trajectories, motivations, and digital competence of students. That is why the fractal approach makes it possible to substantiate the need to model a digital university as a system that is in constant self-development, self-organization, and multilevel interaction with the external environment.

A digital university functions within a socio-economic system where goals, objectives, and expectations are constantly changing under the influence of technological, political, and social factors [9, p.6]. The hierarchy of educational subsystems - from the department to the ministry - has signs of fractal similarity: the same management logic is implemented at different scale levels. This is the potential of the fractal approach to regulation - it allows for the implementation of strategic solutions that are scalable, adaptive, and sustainable, regardless of the level of the system. It is fractality that allows a digital university to function not as a rigid vertical structure, but as a flexible ecosystem with integrated educational, managerial, and economic processes.

Modeling educational activity and its management system within a digital university requires the formalization of a wide range of concepts that are often interpreted arbitrarily in scientific and applied discourse. The objective basis for analytical comprehension is made up of statistical information, formed models of multi-level management, and the identified deficit of prognostic tools in the “education - personnel - competencies” chain. This necessitates the use of substantiated mathematical and economic-analytical approaches to unify evaluation criteria and select optimal solutions. A comparative analysis of the relevant methods is presented in Table 1.

Table 1.

Comparative analysis of methods for reducing criteria to a single score

Method	Advantages	Limitations
Principal component analysis	Allows for representation of the studied system behavior as a set of statistically independent components, which facilitates modeling with a reference model and comparison with the real system. Effective for dimensionality reduction in multidimensional data.	The economic interpretation of the principal components is difficult to ensure. The parameter estimates are formed not by the primary variables, but by the transformed ones.
Method of a complex criterion for a fair compromise	Easy to calculate: the best option is determined by the maximum value of the product of individual criteria.	Not all criteria are equivalent; the method is focused on a narrow range of tasks.
Method for constructing and analyzing the Edgeworth-Pareto set	Allows for solving multi-criteria selection problems; allows for creating a space of Pareto-efficient solutions.	The Pareto set is often too large; a specific solution within the set is not unambiguous. For a practical choice, an additional selection of one of the optimums is required.

** Compiled by the author based on sources [6;7;8]*

The cluster nature of educational structures, their fractal organization on the principle of self-similarity, as well as the agent-based nature of the interaction between participants in the educational process, determine the feasibility of using in this research field methods of analyzing fractal and cluster sets, multi-agent systems, as well as intelligent management and decision-making systems, taking into account the strategic priorities of higher education institutions. This allows for the modeling of a digital university as a complex self-organized educational and economic system.

The first group of decision-making methods in the context of digital university management can be mathematically formalized as vector optimization problems, including the construction of objective functions and performance criteria. The second group of methods is the tasks of classifying and ranking alternatives based on integral indicators. A comparative analysis of such methods is presented in Table 2.

The fractal approach to modeling a digital university can be scientifically substantiated only in the case of systems that are in a state of development and have the property of self-similarity. In this context, a fractal multiple formation is considered as a set of interconnected structures of different hierarchical levels that arise and transform as a result of internal and external factors. Such structures are capable of self-development, self-organization, and the production of new subsystems, which are characteristic of the educational and economic ecosystem of a digital university.

Each educational structure within a digital university, including departments, institutes, faculties, administrative units, and inter-university associations, can be considered as a fractal element of a more general level. They produce information flows of data, knowledge, decisions, and competencies that form the basis for adaptive management at various scale levels. At the same time, sets of big educational data

partially have a fractal structure, which is manifested in cases of joining new participants, transforming old elements, or creating new functional blocks within the educational environment.

Table 2.

Comparative analysis of decision-making methods in the system of training of digital university staff

Method	Advantages	Limitations
Multi-criteria utility theory	Ensures mathematical rigor in the selection of solutions, allows for ordering alternatives by level of preference. Models not only optimal but also compromise solutions.	Difficulty in constructing a utility function; difficulty in verifying the independence of criteria and determining their weight.
Analytic hierarchy process (AHP)	Allows for checking the consistency of expert opinions, adjusting pairwise comparison matrices, and ensuring the stability of rating results.	High complexity of data preparation; difficulty in reaching consensus among experts.
Methods for ranking multi-criteria alternatives	Effective in group decision-making, allow for ordering all alternatives by importance; characterized by simplicity, efficiency, and low costs.	In 10% of cases, there may be contradictions due to non-transitivity of expert preferences; subjectivity of assessment; the method does not quantify the distance between alternatives.

** Compiled by the author based on sources [6;7;8]*

The presence of fractal similarity of educational structures at different levels provides clear conditions of interaction for all agents. However, identifying such structures, observing them, assessing the life cycle phase, and predicting the development of the digital university ecosystem remains a difficult task. That is why there is a need to create fractal-type system models that would allow linking a certain set of indicators to each level of the hierarchy in the form of time series, expert opinions, ratings, sociological research data, etc. in a formalized form, such as:

$$a\frac{k}{ij}, \quad (1)$$

where:

k – number of the hierarchical level of the structure,

i – number of the indicator,

j – number of the indicator value.

To further formalize the evaluation of the structural elements of the digital university, it is advisable to normalize the initial data. Let us denote normalized indicators as $x\frac{k}{ij}$, where k– is the number of the hierarchical level, i – is the number of the indicator, j – is a specific value. In this case, the values of normalized data will be

in the range $0 \leq x\frac{k}{ij} \leq 1$. For positively interpreted indicators (the more, the better), normalization is performed by the formula:

$$x\frac{k}{ij} = \frac{a\frac{k}{ij} - \min a\frac{k}{ij}}{max\ a\frac{k}{ij} - \min a\frac{k}{ij}}, \quad (2)$$

For negative ones (the less, the better):

$$x\frac{k}{ij} = \frac{max\ a\frac{k}{ij} - a\frac{k}{ij}}{max\ a\frac{k}{ij} - \min a\frac{k}{ij}}, \quad (3)$$

Such normalization preserves monotony: the closer the value is to one, the higher the quality of the relevant educational and economic parameter.

Considering the limited accuracy, incompleteness, and heterogeneity of educational statistics, it is advisable to form integral characteristics - indices, ratings, and performance indicators - for each hierarchical level of a digital university. An effective method for reducing the dimensionality of data and identifying key factors is the principal component analysis. A compressed index that aggregates the most informative principal components can be calculated using the formula:

$$I_j = \sum_{p=1}^{r} \lambda pYpj, \quad (4)$$

where: Ypj – principal components, λp– weighting coefficients. Visually, the data transformation process is described in the following scheme:

X→Y→1.

where:

X – matrix of initial indicators (measurements of educational and economic activity),

Y– principal component matrix,

I – vector of integral indices.

This class of models is knowledge-oriented, where the main task is to provide a concise, relevant description of complex input parameters (educational trajectories, digital competencies, resource load, and management indicators). In addition to the principal components, the following can be used: methods of correlation and regression analysis, extreme grouping (clustering), and construction of centers of gravity (centroids) - as representatives of groups of parameters at a certain level of the hierarchy. Such centroids are fractal analogs of reference structures suitable for comparison, monitoring, and forecasting.

In the digital environment, the temporal characteristics of processes acquire signs of a fractal behavioral pattern, which is manifested through structural self-similarity in time series (intensity of interactions, fluctuations in educational metrics, user activity on platforms, etc.).

These series include: aggregated principal components, rating dynamics, performance indices, digital footprints in educational environments, and social communications. All these data, together with algorithms for their processing, acquire the properties of educational and analytical knowledge.

Metadata, big data, and analytical modules based on artificial intelligence technologies are the basis for the management decision support system. The involvement of a posteriori, precedent, and analytical information allows for strategic regulation of the digital university as a fractal ecosystem at all levels, from local to global.

Due to the fractal nature of the data describing educational and economic processes, it is advisable to use methods of analog modeling and inference by precedents for forecasting. This approach allows us to extrapolate patterns to higher levels of the hierarchy, identify risks, synchronize educational and managerial dynamics, and justify optimal strategic decisions. Time series analysis in such a system is the basis for building macro models of a digital university based on microstructured, localized fractal data of educational and economic activity.

It can be stated that the fractal approach to the analysis of the educational and economic ecosystem of a digital university is a methodologically substantiated and practically relevant tool for strategic regulation in the conditions of digitalization. Its use will allow for combining the complex hierarchical structure of educational processes with modern methods of data analysis, in particular through normalization of indicators, aggregation of principal components, construction of integral indices, and use of precedent modeling.

The self-similarity, multi-level repeatability, and temporal patterns inherent in digital universities not only illustrate the fractal nature of educational structures but also provide a basis for building flexible management models. This approach forms the basis for making decisions that are scalable, adaptive, and sustainable, which, in turn, contributes to the efficiency of the educational environment, the development of intellectual capital, and the sustainability of digital universities as complex socio-technical systems.

Conclusions and prospects for further research. As a result of the research, it has been found that the fractal approach has significant potential for strategic modeling and management of the educational and economic ecosystem of a digital university. Its application allows taking into account the self-similarity, multi-level, hierarchical, and behavioral complexity of educational structures in the digital environment.

The fractal model of the university promotes the effective use of educational and analytical data that combines classical statistical indices, expert opinions, and data from digital platforms. The proposed approach opens up opportunities for building a system of strategic regulation adaptive to changes in the environment, social demands, and challenges of digital transformation.

Further research could be aimed at developing applied fractal management models based on aggregated data from educational platforms, big data analytics, and digital interaction indicators. Particular attention should be paid to improving normalization algorithms, calculating centers of gravity in multilevel educational systems, developing fractal-oriented digital dashboards for university management, and identifying key phases of the life cycle of the educational and economic ecosystem. This approach can provide a new quality of management decisions in the face of the growing complexity of the digital educational environment.

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