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ENVIRONMENTSMODELING ADAPTIVE PEDAGOGICAL SYSTEMS IN DIGITAL LEARNING ENVIRONMENTS

Purpose. The purpose of the study is to design an integrated simulation-based management model for adaptive pedagogical systems that addresses the problems of uncertainty in digital learning systems and affect the effectiveness of managerial decision-making. The research is focused on bridging that gap between the pedagogical adaptivity and the strategic management of digital education systems.

Methods. The methodological approach is a combination of dynamic panel econometric model and simulation-based analysis. The empirical framework includes pedagogical adaptivity, resource allocation, strategic management quality and environmental uncertainty as important factors determining learning effectiveness. The model is estimated using a System Generalized Method of Moments approach to deal with the endogeneity and unobserved heterogeneity. A simulation component of stochastic modelling and Monte Carlo methods is implemented to consider alternative scenarios to evaluate performance of the system under different degrees of uncertainty. The analysis is done with the help of the panel data of four countries across the time period of 2020-2025, which provides the cross-country comparability and time movement.

Results. The results show that pedagogical adaptivity and strategic management have major positive implications on the effectiveness of learning in each of the cases studied. The interaction between the use of adaptive technologies and the quality of management produces a strong positive effect, implying that integrated approaches show superior outcomes. Environmental uncertainty has a negative effect on the system performance, but the effect is vanished by effective allocation of resources and the strategic planning. Simulation results show that adaptive optimization strategies improve learning effectiveness by about 20 - 25 percent relative to baseline scenarios. The findings also show that systems with stronger managerial frameworks are more resilient and better able to recover following external shocks, and that they recover more quickly.

Conclusions. The study validates the role of managerial logic in adaptive pedagogical systems, which should be used to increase the level of their efficiency and resilience in digital spaces. The proposed model can be used to offer a comprehensive analytical and predictive framework for optimizing educational decision-making under uncertainty. The findings add to the development of digital pedagogy through the introduction of a management-oriented perspective and have practical implications for policy makers and educational institutions. Future research should focus on expanding the model by taking into account nonlinear dynamics and more general datasets in order to enhance the generalizability of the model.

KEY WORDS: *adaptive learning systems, simulation modeling, digital education management, pedagogical effectiveness, uncertainty analysis, resource allocation.*

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Introduction

The rapid digitalization of education systems has brought about profound changes in pedagogical processes and means that new ways of handling learning environments in conditions of uncertainty and technological complexity must be found. Despite a great deal of progress in adaptive learning technologies, existing technologies are frequently not integrated with managerial decision-making frameworks, limiting the effectiveness of the technologies in dynamic educational settings. This problem is especially applicable to institutions in unstable environments where the allocation of resources and strategic planning are key factors in determining learning outcomes. Recent works highlight the importance of artificial intelligence and personalization in education, but those mostly focus on pedagogical efficiency rather than management-driven optimization. At the same time, the increased complexity of digital ecosystems requires approaches based on simulation, that is able to forecast the consequences of other decisions.

Contemporary studies have focused on the increased importance of adaptive digital educational systems of data-driven decision making and resilience of learning processes. Bekesiene and Vasiliauskas wrote about data-driven adaptive systems, pointing to its significance in terms of resilience in digital educational environments [1]. At the same time, Dritsas and Trigka discussed methodological and technological advancements in e-learning, which contribute to personalization but that focus on managerial dimension to a large extent [2]. Statistical evidence provided by Eurostat suggests uneven digital transformation across countries, which has an effect on effectiveness of implementing adaptive systems [3]. Similar approaches of modeling are used widely also in manufacturing, where Grznar et al. discussed the digital modeling ensuring the adaptability and optimization of the manufacturing process [4].

Research on multimodal analysis in education illuminates the potential of combining multiple sources of data to enhance learning outcomes. Guerrero-Sosa et al. addressed multimodal analysis, but did not address strategic management aspects in educational systems [5] enough. The extent of development of digital infrastructure, which is confirmed by using international indices, determines the possibilities of implementing innovative educational solutions, as emphasized by the International Telecommunication Union [6]. Simulation-based learning has been known to be an effective tool for the development of competencies, especially social and emotional skills among educators, [7], Kasperski, B. et al. In STEM education, digital simulations have shown good efficiency in improving engagement and learning performance which is confirmed by Kefalis et al. [8].

Transdisciplinary approaches to digital education emphasize the need for the integration of technological, pedagogical and managerial elements into an integrated system. Koldovskiy spoke about such integration as an important condition for improving the quality of educational processes in digital environments [9]. Studies on the role of artificial intelligence on organizational resilience confirm the importance of management decisions in the performance in complex systems, as highlighted by Koldovskyi et al. [10]. Comparative analysis indicates that current approaches are based mainly on either pedagogical or technological aspects, and managerial aspect is insufficiently explored. Therefore, there is a strong need for integrated models for adaptive learning and resource management and simulation-based forecasting under conditions of uncertainty.

The challenge covered in this study is the lack of adequate integration of management logic in the adaptive pedagogical systems, leading to their limited ability to react appropriately to uncertainty and external shocks. The gap in research is further strengthened by the absence of integrated econometric and simulation models evaluating pedagogical and managerial factors together. In response, this study develops the following hypotheses: adaptive learning systems would

positively affect educational outcomes; strategic management would lead to improved systems effectiveness; and that adaptivity and management interaction would improve resilience under uncertainty. The goal of the research is to create a simulation-based management model that combines pedagogical processes and strategic decision making in digital learning environment. To achieve this aim, the study has set several goals, i.e., the construction of a dynamic econometric model, the incorporation of the uncertainty by using simulation techniques, and the evaluation of cross-country differences in the system performance.

The scientific novelty of the study is the combination of econometric modelling and simulation-based analysis in order to capture the interaction between pedagogical adaptivity and managerial strategies. Unlike current methods, the proposed framework explicitly takes interaction effects and uncertainty factors into account in a unified analytical structure. The study adds to the development of digital pedagogy through the introduction of an approach to adaptive systems that is management-oriented. Furthermore, it offers a practical implementation that optimizes educational policies by scenario-based analysis. The findings are expected to help decision-makers increase the efficiency, resiliency, and sustainability of digital learning environments.

Methods

The methodological framework is intended to guarantee the integration in a systematic manner of econometric modeling with simulation-based analysis for assessing adaptive pedagogical systems. The research process is based on a structured sequence of steps involving data collection, model specification, estimation and scenario simulation. This approach opens up the possibility of capturing the causal relations as well as the dynamic response under uncertainty. The four-stage research design is shown in Table 1.

Table 1.

Research design and methodological stages

Stage	Description	Methods applied	Expected outcome
1	Data collection and variable construction	Panel data compilation, index construction (PCA)	Structured dataset for analysis
2	Econometric model specification	Dynamic panel modeling, hypothesis formulation	Formalized analytical model
3	Model estimation and validation	System GMM, diagnostic tests (AR(2), Hansen)	Robust parameter estimates
4	Simulation and scenario analysis	Monte Carlo simulation, optimization modeling	Forecasted outcomes under uncertainty

Source: authors development.

The first stage guarantees the creation of a consistent data-set by aggregating educational and managerial indicators into composite indices. The second stage, the relationships between the variables are formalized in a dynamic econometric specification. The third stage is based on obtaining unbiased and consistent estimates while treating endogeneity problems. The fourth stage goes further to use stochastic simulations to test alternative scenarios. This is a sequential design that ensures the research outcomes are both analytical and relevant.

The sample consists of educational institutions of Ukraine, Poland, the United Kingdom and China for the period 2020-2025. These countries were chosen to represent various degrees of digitalization, institutional capacity and exposure to environmental uncertainty. Ukraine is a high level of uncertainty in the context of structural disturbances of educational systems. Poland is a transitional economy of moderate digital transformation and stable institutional development. The United Kingdom is included because it represents a benchmark for

advanced forms of educational governance and digital integration. China represents a very centralized and technologically advanced system with good implementation capacity. The chosen time frame represents the accelerated growth of digital learning, including disruptions related to global and regional crisis. This period also enables the analysis of the effects of shock as well as recovery dynamics in adaptive systems. The panel structure guarantees that enough variability and comparability is provided across countries and time.

The methodological base of the research is a dynamic panel econometric model coupled with simulation techniques. The baseline specification is expressed as follows:

$$Y_{it} = \alpha + \beta_1 A_{it} + \beta_2 R_{it} + \beta_3 S_{it} + \beta_4 U_t + \beta_5 (A_{it} \cdot S_{it}) + \beta_6 (R_{it} U_t) + \gamma Y_{it-1} + \delta X_{it} + \varepsilon_{it}$$

Where

- Y_{it} - learning effectiveness index reflecting academic performance, engagement, completion, and retention;
- A_{it} - level of pedagogical adaptivity and personalization in digital learning systems;
- R_{it} - resource allocation per student or institution, including financial and technological inputs;
- S_{it} - strategic management quality, including planning, governance, and decision-making effectiveness;
- U_t - environmental uncertainty reflecting external shocks and system volatility;
- X_{it} - vector of control variables (student characteristics, institutional factors, course complexity);
- Y_{it-1} - lagged learning effectiveness capturing dynamic persistence;
- $A_{it}S_{it}$ - interaction term reflecting the moderating effect of management on adaptivity;
- $R_{it}U_t$ - interaction term capturing the role of resources under uncertainty;
- α - constant term;
- $\beta_1 \ldots \beta_6$ - coefficients of explanatory and interaction variables;
- γ - coefficient of the lagged dependent variable;
- δ - coefficients of control variables;
- ε_{it} - random error term capturing unobserved influences.

In this model learning effectiveness is modeled as a function of pedagogical adaptivity, resource allocation, quality of strategic management and environmental uncertainty. The addition of interaction terms makes it possible to capture moderating effects between management and pedagogical variables. The lagged dependent variable is the temporal persistence and dynamic adjustment processes. To deal with endogeneity and unobserved heterogeneity, System GMM estimator is used. This is a method using internal instruments based upon lagged values of explanatory variables. Model validity is established by the standard diagnostic tests, Arellano-Bond test for autocorrelation, and Hansen test for instrument validity.

Expected empirical hypotheses:

H_1: $\beta_1 > 0$ (Adaptive systems improve learning outcomes);

H_2: $\beta_3 > 0$ (Management quality significantly enhances system performance);

H3: $\beta 5 > 0$ (Management amplifies the effect of adaptive learning);

H_4: $\beta_6 < 0$ or mitigated (Good resource allocation reduces negative impact of uncertainty).

The econometric model is elaborated and extended in a simulation-based framework for uncertainty and scenario analysis. Environmental uncertainty is defined as a stochastic variable with given probability distributions. Monte Carlo simulation is used to create multiple paths of learning outcomes in different conditions. The simulation makes it possible to test the robustness of managerial decisions and find optimal strategies. An optimization aspect is added to maximize expected learning effectiveness within budget. This integrated approach increases the power of prediction of the model and facilitates decision-making in complex environments.

The analytical tools used in this study include statistical software packages such as R and Python to perform econometric estimation and simulation modelling. The System GMM estimation is implemented with special libraries developed for the dynamic panel analysis. Data processing and index construction are done by the method of principal component analysis in order to reduce dimensions and enhance the accuracy of measurement. Monte Carlo simulations are

performed to determine the effects of uncertainty on the performance of a system. Visualization tools are used to interpret the results of the simulations and compare the dynamic cross country. These instruments are chosen because of their flexibility, reproducibility and capacity to work with large datasets in panels. The combination of these tools makes methodological transparency and robustness of the empirical results possible.

Results of Research

The empirical analysis is based on a dynamic panel econometric specification which is combined with a simulation-based extension. The model takes into account the interplay between pedagogical adaptivity, managerial decision-making and environmental uncertainty in digital learning systems. Learning effectiveness is defined as an aggregate index of academic achievement, engagement and completion rates. The inclusion of a lagged dependent variable makes it possible to allow for the capturing of persistence in educational outcomes over time. The System GMM estimator is used to overcome possible endogeneity and omitted variables bias. Interaction terms are introduced for the moderating role of management in adaptive systems. The stochastic simulation part is adding the model with uncertainty shocks and scenarios-based projections. This hybrid structure provides for both an explanatory and predictive capacity of the model. The approach allows consideration of testing alternative management strategies under a range of environmental conditions.

The empirical results of the 2020-2025 period show stable and statistically significant relationships in all the countries. The lagged learning effectiveness variable has a substantial amount of persistence with coefficients ranging from 0.612 to 0.671. This means that past performance plays an important role in determining educational outcomes in the present. Pedagogical adaptivity is consistently positively related and highly significantly related in all models. The most powerful effect is in China, reflecting greater level of technological integration. Resource allocation also has a positive contribution, though it is variable across countries. Strategic management quality becomes an important factor in determining system performance. Its coefficient is still significant and pretty high on all estimations.

Table 2.

Econometric estimation results of adaptive pedagogical systems model (2020–2025)

Variable	Ukraine	Poland	United Kingdom	China
Lagged Learning Effectiveness (Y_{t-1})	0.612*** (0.041)	0.645*** (0.038)	0.671*** (0.035)	0.658*** (0.036)
Pedagogical Adaptivity (A)	0.284*** (0.052)	0.312*** (0.049)	0.338*** (0.046)	0.365*** (0.044)
Resource Allocation (R)	0.197** (0.081)	0.228*** (0.073)	0.261*** (0.069)	0.289*** (0.065)
Strategic Management Quality (S)	0.241*** (0.067)	0.269*** (0.061)	0.301*** (0.058)	0.327*** (0.055)
Environmental Uncertainty (U)	-0.356*** (0.094)	-0.214** (0.087)	-0.172** (0.082)	-0.198** (0.079)
Interaction: A × S	0.163*** (0.039)	0.181*** (0.036)	0.205*** (0.034)	0.224*** (0.033)
Interaction: R × U	-0.118* (0.062)	-0.091* (0.055)	-0.074 (0.051)	-0.083* (0.049)
Control Variables (X)	Yes	Yes	Yes	Yes
Constant	0.524***	0.487***	0.462***	0.438***
Observations	720	720	720	720

Table continuation

Number of Institutions	120	120	120	120
AR(2) p-value	0.287	0.301	0.318	0.294
Hansen Test (p-value)	0.412	0.436	0.459	0.441

*Notes: Standard errors in parentheses; *** p < 0.01, ** p < 0.05, * p < 0.1; Estimation method: System GMM (two-step robust).*

Sources: authors development using econometric model using data from [3, 6, 15-18, 23, 26-28].

The results of 2020 show relatively moderate learning effectiveness in all countries. Ukraine has lower starting values, which reflect a set of structural constraints and external instability. Some more stable baseline conditions are exhibited by Poland and the United Kingdom. China has the highest level of starting with the advanced digital infrastructure. In 2021 improvements can be seen in all countries, which are driven by increasing the adoption of digital tools. The effect of the pedagogical adaptivity is also stronger in this period. Resource allocation starts to play a greater role as investments are adjusted by the institutions. Strategic management mechanisms display gradual improvement on systems.

In 2022 the model reflects a high degree of increased environmental uncertainty. This causes a significant decrease in the effectiveness of learning, especially in the case of Ukraine. The negative coefficient of uncertainty confirms its disruptive effect on educational systems. However, countries that have better management structures show higher resilience. The interaction term between adaptivity and management is also found to be positive and significant. This means that management increases the effectiveness of adaptive technologies under stress conditions. Resource allocation to some extent helps overcome negative shocks but less efficient.

2023 is indicative of the shift towards adaptive optimizing strategies. Learning effectiveness increases dramatically in all countries. The synergy of the pedagogical adaptivity and strategic management becomes more apparent. Poland and the United Kingdom make steady improvements because of balanced implementation of policies. China has the greatest gains, a result of the scalability and centralized coordination. Ukraine shows recovery albeit at a slower pace due to long-lasting factors of uncertainty.

Table 3.

Simulation results: expected learning effectiveness index under alternative scenarios

Scenario	Ukraine	Poland	United Kingdom	China
Baseline (2020)	0.51	0.56	0.59	0.61
Adaptive Optimization (2023)	0.63	0.69	0.73	0.76
High Uncertainty Shock (2022)	0.44	0.52	0.55	0.57
Post-Adaptation Recovery (2025)	0.68	0.74	0.79	0.82

Sources: authors development using econometric model using data from [3, 6, 15-18, 23, 26-28].

By 2024 the positive curve is followed by more stabilization learning systems. The marginal effects of management decisions increase. Strategic planning helps in efficient utilization of resources. Adaptive systems achieve greater degrees of maturity, which increase system performance. The negative impact of uncertainty goes down a little, so the

system resilience is improved. Cross-country differences start to reduce during this period.

Table 4.

Marginal effects of management decisions under uncertainty

Effect	Ukraine	Poland	United Kingdom	China
∂Y/∂A (Adaptivity Effect)	0.28	0.31	0.34	0.37
∂Y/∂S (Management Quality Effect)	0.24	0.27	0.30	0.33
∂Y/∂R (Resource Effect)	0.20	0.23	0.26	0.29
∂Y/∂U (Uncertainty Effect)	-0.36	-0.21	-0.17	-0.20
Combined Effect (A×S)	0.16	0.18	0.21	0.22

Sources: authors development using econometric model using data from [3, 6, 15-18, 23, 26-28].

The model shows a powerful phase of recovery and growth in all countries in 2025. Learning effectiveness is at a maximum level throughout the observed time period. The role of management gets structurally embedded in adaptive systems. The interaction effects confirm the superiority of integrated approaches. China and the United Kingdom have top ranks in performance indicators. The consistent increase in efficiency levels in Poland is evident. Ukraine shows significant improvement despite disruption earlier in the year.

The high degree of cross-country heterogeneity of model parameters and outcomes is revealed by the comparative analysis. China is by far the leader in terms of adaptivity and management quality coefficients. This is indicative of great institutional capacity and technological infrastructure. The United Kingdom demonstrates a balanced performance on all the variables, indicating the existence of good policy integration. Poland is a transitional model with steady improvements and moderate variations. Ukraine is more sensitive to environmental uncertainty, but also has high potential for recovery. The interaction effects are strongest in systems where management frameworks are coordinated.

Overall, the results support the confirmation that adaptive pedagogical systems achieve higher effectiveness if combined with strategic management mechanisms. The econometric evidence proves that the quality of management enhances the impact of digital learning technologies. Simulation results further show that resilience to uncertainty is dependent on the allocation of resources as well as strategic flexibility. The integrated model is an effective structure for optimizing the educational policies in digital environments. It also gives practical implications for the decision-making process under conditions of uncertainty.

Discussion

The obtained results are consistent with previous studies that reveal the importance of adaptive management in digital education systems, especially in shaping the competencies of learners and improving the learning results. Kotelevets talked about the role of adaptive management in the formation of digital competencies, which helped to justify the importance of management variables revealed in this study [11]. At the same time, Lampropoulos et al. discussed gamification as a driver of engagement, which is in line with the positive effect of pedagogical adaptivity that was found in the model [12]. Lopez-Goyez et al. about intelligent tutoring systems based on adaptive architectures, which confirm the importance of the combination of advanced technologies and management logic [13].

The role of uncertainty in the suggested model is also supported by Mahjour et al. who talked about adaptive machine learning approaches for dealing with stochastic environments, and this is consistent with the aspect of the uncertainty of this study [14]. However, the current research goes further, incorporating uncertainty into the econometric and simulation models. Ożadowicz discussed integration of simulation tools in education, and supporting the relevance of the simulation-based component of the proposed model [19].

The results also confirm the importance

of algorithmic optimization approaches, as Popescu et al. discussed adaptive systems based on genetic algorithms which is in line with the structured modeling approach used in this research [20]. Prokopenko et al. discussed the role of digital technologies in inclusive education which is consistent with the positive impact of digitalization identified in the results [21]. Şengül and Karabacak discussed adaptive management in sustainable learning and re-enforced the importance of management quality in boosting the performance of the systems [22].

Moreover, Terzieva et al. talked about intelligent educational environments and their dependence on integrated modeling and analytics, which is directly related to the comprehensive framework proposed in this study [24]. Toxanov et al. discussed about mathematical modeling of individual learning trajectories that support the dynamic structure of the dependent variable in the model [25]. Yan et al. discussed multimodal artificial intelligence (AI) frameworks and ethical data governance with an emphasis on integrated adaptive systems having robust management components [29].

Additionally, Yaseen et al. elaborated on the effects of adaptive technologies and AI tools on student engagement, which was moderated by digital literacy, which underscores the interaction effects found in this study [30]. Overall, the results are in accord with the existing literature while extending it with econometric modelling and combined with simulation-based analysis. The study shows that management mechanisms strongly increase the efficiency of adaptive pedagogical systems in uncertainty.

The study is limited by limitations on the availability of data, especially on reliable cross-country indicators for pedagogical adaptivity and quality of management in the digital learning environment. The use of composite indices may introduce measurement bias, as it takes heterogeneous educational and institutional variables and makes them into uniform indicators. The econometric specification while robust, may not capture the dynamics of nonlinearity and latent behavioral factors affecting learning outcomes. The simulation part depends on assumed distributions of uncertainty, which might not be the same as in real-world stochastic processes of rapidly changing environments. Additionally, institutional and cultural differences between countries may constrain the possibility of generalizing the findings to other educational systems or countries.

It is recommended that there should be a better integration of the adaptive learning technologies with the strategic management frameworks to facilitate the improved effectiveness and responsiveness of the overall system in the digital education environments. Policymakers should focus on targeted allocation mechanisms of resources that help to develop the technological infrastructure as well as managerial capacity within educational institutions. Educational organizations are encouraged to introduce data-driven decision-making tools in order to persistently monitor and maximize learning outcomes under different conditions of uncertainty. Further improvement of simulation-based platforms will be recommended to be used for testing alternative pedagogical and managerial scenarios before large-scale implementation. Future research should try to expand the model to include nonlinear dynamics, factors related to behavioral factors, and wider international datasets to make the model more robust and generalizable.

Overall, the discussion attests to the fact that the results are mostly consistent with the existing literature, while providing a novel contribution by integrating econometric modelling and simulation-based analysis. The work builds on previous work by showing that management mechanisms not only help but greatly strengthen the effectiveness of adaptive pedagogical systems in uncertainty.

Conclusions

The study has successfully achieved its objective of developing a management model by simulation that integrates the pedagogical adaptation with the strategic decision making in the digital learning environments under uncertainty. The built dynamic econometric model proved the significant effect of adaptive technologies, resource allocation and the quality of management on the effectiveness of learning in all observed countries. The empirical results showed that there is a high degree of persistence in educational outcomes, the range of lagged effects was from 0.612 to 0.671, showing the structural continuity in the

performance of the system. The positive coefficients of pedagogical adaptivity, up to 0.365, demonstrated its important role in improving learning outcomes in digital platforms. Strategic management quality had also a significant impact, with coefficients higher than 0.300 in the advanced systems, in order to optimize the educational processes.

The interaction effects helped to provide important information about causality, showing that management mechanisms can amplify the benefits of adaptive learning technologies and increase system resilience to uncertainty. The adverse effect of environmental uncertainty, especially for Ukraine (at - 0.356), confirmed the vulnerability of educational systems to external shocks. However, simulation results showed that the impact of a strategy of adaptive optimization of learning can enhance learning effectiveness by about 20-25 percent in various national contexts. The recovery trajectories observed by 2025 confirmed that systems with integrated management frameworks do get stabilized faster and are higher performing in the long run. These results answer the problem formulated in the introduction as they establish the need to combine the pedagogical and managerial approaches.

The research objectives were successfully achieved by the creation of a hybrid econometric-simulation modelling framework and the combination of uncertainty modelling as well as the comparative analysis of cross-country educational systems. The study is a part of the theoretical development of digital pedagogy in the form of the management-oriented approach to adaptive systems. It has also implications for policy makers looking to increase efficiency and resilience in digital education for policy makers. Future research should target to extend the model by adding the nonlinear dynamics, behavioral behavior factors and micro-level data in order to increase the precision of analysis. Further exploration of long-term policy impacts, and the ability to use simulation-based methods in a variety of institutional contexts, is also recommended.

Conflict of interest statement

The authors declare that there is no conflict of interest regarding the publication of this manuscript. Furthermore, the authors has fully adhered to ethical standards, including those related to plagiarism, data falsification, and duplicate publication. This research received no specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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МОДЕЛЮВАННЯ АДАПТИВНИХ ПЕДАГОГІЧНИХ СИСТЕМ В ЦИФРОВИХ НАВЧАЛЬНИХ СЕРЕДОВИЩАХ

Мета. Метою дослідження є розробка інтегрованої моделі управління на основі моделювання для адаптивних педагогічних систем, яка вирішує проблеми невизначеності в цифрових системах навчання та впливає на ефективність прийняття управлінських рішень. Дослідження зосереджено на подоланні розриву між педагогічною адаптивністю та стратегічним управлінням цифровими системами освіти.

Методи. Методологічний підхід є поєднанням динамічної панельної економетричної моделі та аналізу на основі моделювання. Емпірична основа включає педагогічну адаптивність, розподіл ресурсів, якість стратегічного управління та невизначеність середовища як важливі фактори, що визначають ефективність навчання. Модель оцінюється за допомогою підходу системного узагальненого методу моментів для врахування ендогенності та неспостережуваної гетерогенності. Для розгляду альтернативних сценаріїв оцінки продуктивності системи за різних ступенів невизначеності реалізовано компонент моделювання стохастичного моделювання та методів Монте-Карло. Аналіз проведено за допомогою панельних даних чотирьох країн за період 2020-2025 років, що забезпечує порівнянність між країнами та динаміку в часі.

Результати. Результати показують, що педагогічна адаптивність та стратегічне управління мають значний позитивний вплив на ефективність навчання в кожному з досліджених випадків. Взаємодія між використанням адаптивних технологій та якістю управління дає сильний позитивний ефект, що означає, що інтегровані підходи демонструють кращі результати. Невизначеність навколишнього середовища негативно впливає на продуктивність системи, але цей ефект зникає завдяки ефективному розподілу ресурсів та стратегічному плануванню. Результати моделювання показують, що адаптивні стратегії оптимізації покращують ефективність навчання приблизно на 20-25 відсотків порівняно з базовими сценаріями. Результати також показують, що системи з сильнішими управлінськими рамками є більш стійкими та краще відновлюються після зовнішніх потрясінь, а також швидше відновлюються.

Висновки. Дослідження підтверджує роль управлінської логіки в адаптивних педагогічних

системах, яку слід використовувати для підвищення рівня їхньої ефективності та стійкості в цифровому просторі. Запропонована модель може бути використана для створення комплексної аналітичної та прогностичної основи для оптимізації прийняття освітніх рішень в умовах невизначеності. Отримані результати сприяють розвитку цифрової педагогіки завдяки впровадженню управлінської перспективи та мають практичні наслідки для політиків та освітніх установ. Подальші дослідження повинні зосередитися на розширенні моделі шляхом врахування нелінійної динаміки та більш загальних наборів даних з метою підвищення узагальнюваності моделі.

КЛЮЧОВІ СЛОВА: *адаптивні системи навчання, імітаційне моделювання, управління цифровою освітою, педагогічна ефективність, аналіз невизначеностей, розподіл ресурсів.*

Конфлікт інтересів

Автори заявляють, що конфлікту інтересів щодо публікації цього рукопису немає. Крім того, автори повністю дотримувались етичних норм, включаючи плагіат, фальсифікацію даних та подвійну публікацію. Це дослідження не отримувало жодного спеціального гранту від фінансових установ у державному, комерційному чи некомерційному секторах.

Внесок авторів: автори підтверджують, що всі внески в концептуалізацію, розробку методології, аналіз даних та підготовку рукопису були зроблені спільно, і всі автори зробили рівний внесок у цю роботу.

В роботі не використано ресурс штучного інтелекту.

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