

The subject of this study is the processes of assessing the effectiveness of the implementation of immersive technologies in the systems of sustainable development at universities. The problem that determined the purpose of the work is the lack of methodological tools for assessing the level of efficiency in the implementation of immersive technologies on the basis of sustainable development (using an example of Lviv Polytechnic National University). The authors' toolkit includes a system of indicators, a methodological approach to the use of software for their evaluation, and a matrix for interpreting the results. The choice of the efficiency assessment method is based on the theory of fuzzy sets. The study of the factors influencing the effectiveness of the implementation of immersive technologies in the educational process has made it possible to form a system of integrated indicators, including indicators designed to comprehensively identify its level in the student and teaching environments. The indicator of effectiveness of immersive technologies implemented by students contributes to a thorough analysis of their ability to generate innovations based on such technologies. This indicator allows lecturers to determine the level of effectiveness of the use of immersive technologies in teaching. Taking into account the ideology embedded in the sustainable development systems of universities, the authors' indicators reflect the principles of sustainability. The GE/McKinsey matrix was adapted for the purpose of economic interpretation of mathematical results. The designed methodological tools were tested for courses at the Lviv Polytechnic. The following levels of student performance were obtained: 83.5, 61.5, and 69.8 units, lecturers – 91.2, 78.4, and 82.7 units, which indicates the productivity of lecturer training and a high level of students' understanding of project work tasks. This proved the validity and possibility of using the tools in university practice

Keywords: assessment method, immersive technologies, sustainable development, university development system

ASSESSING THE EFFECTIVENESS OF IMPLEMENTING IMMERSIVE TECHNOLOGIES WITHIN UNIVERSITY SUSTAINABLE DEVELOPMENT SYSTEMS

Viktoriia Prokhorova

Doctor of Economic Sciences, Professor*

Oleksandra Mrykhina

Doctor of Economic Sciences, Professor**

Orest Koleshchuk

Corresponding author

Doctor of Economic Sciences, Associate Professor**

E-mail: orest.y.koleshchuk@lpnu.ua

Tetiana Demianenko

PhD, Associate Professor*

*Department of Economics and Management

V. N. Karazin Kharkiv National University

Svobody sq., 4, Kharkiv, Ukraine, 61022

**Department of Business Economics and Investment

Lviv Polytechnic National University

S. Bandery str., 12, Lviv, Ukraine, 79013

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1. Introduction

The transition of most countries of the world to the paradigm of sustainable development determined a number of prerequisites and requirements for people's lives. This led to the emergence of a new social phenomenon – when practically all domains of life are imbued with the idea of improving quality on the basis of environmental protection, social justice, racial and national tolerance, etc. At the same time, innovative technologies are developing at a rapid pace, which, on the one hand, are designed to contribute to the fulfillment of sustainable development tasks, and on the other, become the basis for the development of newer technologies taking into account the ideology of sustainability. Synergy of progress of technology, business, and society in the context of sustainable development predetermines the advancement of a favorable landscape for achieving sustainable economic growth of countries. The educational environment is one of the defining components of such a landscape because it is in it that the foundations of sustainable development are laid in human consciousness.

Most of the world's leading universities have devised strategies for sustainability, which make it possible to systematize the educational process taking into account the Goals of Sustainable Development of the United Nations. For example, according to [1], as of 2022, more than 1,250 universities in 105 countries had educational programs that take into account various components of the sustainable development goals. Note that in practice the implementation of sustainable development strategies by universities is characterized by certain difficulties because of the need for deep changes in the educational process. This applies both to approaches to teaching material by academic disciplines, and to the content of their content.

One of the teaching techniques based on the ideas of sustainability is the implementation of immersive technologies (systems of virtual (VR), augmented (AR), and other types of reality, simulation of scenarios of the development of events based on educational topics, etc.) in educational processes. This will ensure the transition of universities to the level of an interactive and effective educational envi-

ronment and will meet the modern demands of the market. Using immersive technologies, course participants have the opportunity to save resources and energy in practice, raise awareness of environmental problems, and realize their role in it. The lecturers will introduce the value guidelines of sustainable development into the student curriculum while simultaneously applying teaching methods that correspond to the postulates of sustainability.

The importance of the above is confirmed by the results of a study at the Irish National University (Galway), published in Sustainability [2]. In particular, it is indicated that 91 % of academic staff consider their work important for sustainable development, and 70 % are interested in taking into account the goals of sustainable development in their modules. However, at present, there is not a sufficient number of methods and models of economic evaluation of the effectiveness of the implementation of immersive technologies in universities. The problem of qualitative and quantitative measurement of the level of use of immersive technologies, taking into account the goals of sustainable development, remains unresolved. Most current university sustainability strategies only declare the areas of application of immersive technologies but do not provide the necessary tactics for evaluating their effectiveness.

The relevance and practical significance of the specified problem is confirmed by the benchmarking analysis of a number of universities. For example, the University of California (Irvine, USA) includes sustainability components in more than 50 % of its courses, and more than 96 % of its academic departments offer courses related to sustainable development [3]. About 15 % of all courses at Arizona State University (USA) include fundamental elements of sustainable development, and 95 % of its degree programs include at least one course related to sustainability [3]. At the same time, these universities are actively introducing VR and AR into the educational process. Lund University (Sweden) uses VR for simulations in educational programs [4]. All engineering, science, construction, law, and business degrees at the University of Newcastle (Australia) cover sustainability components based on the use of immersive technologies. [1]. The Georgia Institute of Technology (USA) uses immersive technologies to create virtual laboratories, and also implements the “Sustainability Next” initiative, which includes the integration of sustainable development into educational programs, research, etc. [5]. However, a detailed analysis of these and other universities proves the lack of methodological tools for evaluating the effectiveness of the implementation of immersive technologies in the educational process on the basis of sustainability, even in the presence of sustainable development ecosystems created in most of them.

The lack of methodological tools for evaluating the effectiveness of immersive technologies in universities compromises the understanding of the value of their use in the context of the ideology of sustainability. At the same time, it blurs the boundaries of the categories “expediency/necessity” of using immersive technologies in the educational process. After all, without evaluation, it is not obvious to what level, when and where they should be implemented. Therefore, solving the problems of evaluating the level of effectiveness of the implementation of immersive technologies in the initial processes of universities on the basis of taking into account the provision of sustainable development is relevant and practically significant in the modern system of global innovative progress.

2. Literature review and problem statement

The problems of using immersive technologies in the educational process are widely represented in the fields of modern science and practice, which proves its importance. However, a review of existing publications in the subject field showed a certain fragmentation of research due to the multifaceted nature of this topic. For the most part, it is divided into social and technical contexts. For example, in work [6], an assessment of the ideas of the student society regarding the use of immersive technologies in order to improve the educational process was carried out. This aspect is considered on the basis of interdisciplinary education. The authors, taking into account the recognized pedagogical advantages of using immersive technologies in higher education, substantiated a number of obstacles that require further empirical research, one of the leading ones being the development of methods for evaluating the effectiveness of such technologies. Variants of overcoming the specified obstacles are outlined in work [7], in which a wide range of issues of implementation of immersive technologies in educational studios is covered. The researchers also evaluated student reflections on their implementation. A partial solution to this issue is presented in paper [8]. In this context, scientists have paid considerable attention to the value of an interdisciplinary approach to the organization of education using immersive technologies. This is confirmed by the results of improving the student experience of involvement in the educational process on the basis of immersion, proven in [9]. However, in these works, the goal was not to devise a methodological toolkit for evaluating the effectiveness of the implementation of immersive technologies in universities. In addition, practically nowhere is the use of such technologies to stimulate the sustainable development of educational institutions mentioned.

Our analysis of the array of scientific and practical publications on the subject of methodological support to the implementation of immersive technologies on the basis of sustainable development showed a number of alternative authors' approaches to solving this problem. In particular, new opportunities and prospects for the use of immersive technologies are described in [10]. In work [11], the experience of providing immersive solutions for training courses is considered, where not only traditional training is considered outdated but also modern technologies are insufficient to ensure the optimal quality of teaching. Human perception and immersive technologies are considered by scientists as the main components of learning. In this scientific direction, work [12] should be noted, which presents approaches to the development of VR experiences to support sustainable behavior change based on a systematic review. The authors elaborated on the different functions that need to be managed, the possible alternatives when creating a VR experience, relating them to the behavioral aspects that can be considered, according to the goal of the project. This work can become a tool for research and orientation to sets of optimal solution options, creating individual solutions in the context of the given problem. So, although the above studies substantiated the problem of using immersive technologies in education, methodical ways of solving it were not provided.

The search for answers to the questions is partially reflected in paper [13]. Its authors made an attempt to determine the impact of the metauniverse system by developing

an appropriate conceptual model. The results of the study made it possible to establish the efficiency factors of this system, but without further measuring the level of their influence.

A significant amount of existing analytics covers the issue of immersiveness from the perspective of experience in the application of artificial intelligence technologies. For example, paper [14] is of particular interest, which analyzed the effectiveness of the educational environment based on the model “student – subject – educational process” through the introduction of elements of artificial intelligence. The authors proposed an integrated indicator of the effectiveness of the use of artificial intelligence and an approach to choosing the optimal knowledge assessment system, based on available opportunities. However, the study did not pay attention to the factors of sustainable development.

Attention should be paid to publications that present scientific views on the expediency and effectiveness of immersive technologies in various fields of knowledge, which can contribute to the formation of a holistic vision of this issue. For example, the authors of study [15] developed an evaluation toolkit of the impact of logistics communications, which can be partially applied to immersive technologies. Work [16] highlights the peculiarities of the use of immersive technologies in medical education. In particular, this issue was investigated from the standpoint of a systematic review of the literature in the subject field, the selection of problem areas, based on which the results of learning using immersive technologies were evaluated in comparison with traditional methods. However, both of these studies did not take into account the goals of sustainable development. It is important to reflect the characteristics and parameters of sustainability in the methodological toolkit for evaluating the effectiveness of immersive technologies, which will make it possible to timely and effectively adjust the indicators of sustainable development.

In order to deepen the search for the given problem, publications were considered, which report the results of research on the effectiveness of immersive technologies in the context of specific areas of knowledge or types of activities. For example, work [17] presents the results of the landscape study of the use of augmented and VR technologies in architecture, engineering, and construction. A research program is proposed to address existing gaps in the application of such technologies. This work can serve as a framework for devising methods for evaluating the effectiveness of immersive technologies, but it does not specify a set of tools for this. From such positions, work [18] provides a bibliometric study of the process of global research activity in the field of sustainable development and its dimensions. The approaches to data analytics and the organization of knowledge systems revealed by scientists highlight important aspects of immersiveness, which can become an ideological basis for the development of a methodological toolkit for evaluating the effectiveness of immersive technologies at universities.

The sought-after conceptual aspects on the topic of immersive technologies, which take into account the provisions of sustainable development, are partially given in work [19]. From the point of view of the problem, the value of this work is in the author's models for measuring the level of influence of factors on sustainable development. The research was carried out on the example of the industrial sector, as it makes it possible to transfer individual components to the plane of evaluating the effectiveness of immersive technologies

in education, in particular, when teaching interdisciplinary courses. In this vein, paper [20] reports a case study of the use of immersive technologies to improve effective learning. The article consists of three parts: formation of the digital environment, application of the case in the classroom context, and evaluation of the results. However, the main problem remains open: neglecting the ideas of sustainability, which makes it impossible to obtain results that will enable the system of sustainable development of the university to be supported. Thus, the authors of the above publications substantiate the prospects of immersiveness, emphasize the peculiarities of the use of immersive technologies under the conditions of multifaceted influence of external and internal environmental factors. However, among these publications, there are none that provide specific methods or models for measuring the effectiveness of the implementation of immersive technologies in the educational processes of universities, in particular, based on the principles of compliance with the goals of sustainable development.

These questions were addressed fragmentarily in work [21], which presents the developed methodological toolkit for evaluating scientific and technical developments taking into account the provisions of the concept of sustainable development. A detailed study of the system of evaluation indicators proposed by the authors of this publication made it possible to understand the concepts of taking into account the goals of sustainable development in the specified processes. For these reasons, work [22] developed a holistic system for evaluating scientific and technical products prepared for market launch. The methods proposed in the study are based on the concept of sustainability. A similar opinion is presented in [23], in which a methodical approach to pricing innovative, including immersive, technologies is substantiated. However, this development is only partially applicable to situations of determining the level of immersiveness in university sustainability systems, as its target function is to model the market receptivity of a product. To some extent, the specified articles are complemented by work [24], which reports the results of a comparative study of students' opinions about their IT knowledge and preferences regarding the implementation of augmented reality, VR, blockchain, and artificial intelligence as new learning tools. The work combines the question of the effectiveness of such technologies and taking into account the principles of the concept of sustainable development but does not indicate methods for their evaluation.

Thus, in the presence of certain methodical attempts, the problem of determining the level of effectiveness of the implementation of immersive technologies remains unsolved. The fragmented nature of the development of the given problem does not provide the required methodological basis for further evaluation and justification of relevant management decisions by business entities.

Our review of a significant number of studies on the topic of the implementation of immersive technologies showed that they are practically nowhere considered in the aspect of determining the impact of their introduction by universities on the fulfillment of the goals of sustainable development. The lack of evaluation metrics makes it impossible to justify the level of effectiveness of the implementation of immersive technologies in the educational process. Therefore, even with the successful development of sustainable development systems by universities, in practice they face performance measurement problems.

The implementation of immersive technologies in educational processes is one of the important areas for universities to achieve sustainability. It is important to design such a methodological toolkit for economic evaluation of the effectiveness of the implementation of immersive technologies in the systems of sustainable development of universities, which would be useful in their practice and provide flexible approaches to their strategic management.

3. The aim and objectives of the study

The purpose of our study is to devise a methodological toolkit for economic evaluation of the level of effectiveness of the implementation of immersive technologies in the systems of sustainable development of universities. This will provide, on the one hand, the possibility of analyzing the student's ability to generate innovative solutions based on immersive technologies. On the other hand, it will enable lecturers to determine the level of expediency and effectiveness of using immersive technologies when teaching the material. At the same time, the methodological toolkit will be based on the ideology of sustainability, will contribute to the maneuverability of coordination of methodological components and can be the basis for the formation of measures to implement the strategy of sustainable development of the university, region, and country.

To achieve the goal, the following tasks were set:

- to analyze practical experience of implementing immersive technologies on the basis of sustainable development in the educational process of the university (using the example of Lviv Polytechnic National University);
- to justify the choice of method and devise a system of indicators for evaluating the level of effectiveness of the implementation of immersive technologies on the basis of sustainable development;
- to simulate the interaction of indicators in the system for evaluating the level of effectiveness of the implementation of immersive technologies on the basis of sustainable development;
- to justify the use of the GE/McKinsey matrix approach for the needs of assessing the level of effectiveness of the implementation of immersive technologies on the basis of sustainable development;
- to test the method for evaluating the level of effectiveness of the implementation of immersive technologies on the basis of sustainable development in the educational process of the university (on the example of the Lviv Polytechnic).

4. The study materials and methods

The object of our study is the process of evaluating the effectiveness of implementing immersive technologies in the systems of sustainable development of universities.

In order to achieve the set goal, hypotheses were formed that would make it possible to establish the framework of the research and justify its results.

Hypothesis 1. The methodological toolkit of economic evaluation of the level of effectiveness of implementing immersive technologies in the systems of sustainable development of universities is universal for educational institutions of different countries of the world, programs, and academic disciplines.

Hypothesis 2. The methodological toolkit of economic evaluation of the level of effectiveness of implementing immersive technologies on the basis of sustainable development in the educational process is suitable for use by lecturers who use them as a method of teaching disciplines.

Hypothesis 3. The methodological toolkit of economic evaluation of the level of effectiveness of implementing immersive technologies on the basis of sustainable development in the educational process is suitable for use by students within the scope of their study of educational disciplines.

The Lviv Polytechnic National University serves as the basis for conducting research on the set of problems, in the initial processes of which immersive technologies are actively implemented. The university has devised a development strategy “Lviv Polytechnic-2025” [25], which is based on the goals of sustainable development. For example, most of the modules, which are implemented within the framework of the university's implementation of grant agreements under the EU programs “ERASMUS+” [26, 27], relate to various aspects of the implementation of sustainable development goals.

In the course of conducting this research, several academic disciplines of the Lviv Polytechnic were selected, where the use of immersive technologies is one of the main methods of mastering the material. In order to substantiate the method for evaluating the level of effectiveness of implementing immersive technologies and developing a system of evaluation indicators, the methods of the theory of fuzzy sets (method of fuzzy logic) were chosen. For practical application of the method, the Fuzzy Logic Toolbox component in the MATLAB R2024a software package was used. For the economic interpretation of the results, the adaptation of the GE/McKinsey matrix approach is substantiated.

5. Results of designing methodological tools for evaluating the effectiveness of implementing immersive technologies at universities

5. 1. Analyzing the practical experience of implementing immersive technologies on the basis of sustainable development at the university

Examples of Lviv Polytechnic National University were used to substantiate the results on the topic of this study. In particular, within the framework of the educational program “051 Business Economics”, in the block of university-wide disciplines submitted for selection, “Fundamentals of entrepreneurship and business planning in IT” (bachelor's degree) is offered [28]. In recent years, this discipline has gained popularity among students, which proves its relevance and practical significance. The main idea of the discipline is to teach students the applied principles of entrepreneurial activity, namely justification of business models, strategies for commercialization and scaling of developments, creation and validation of a prototype, marketing and monetization, preparation for a market launch, etc. One of the conditions for evaluating students is their presentation of their development project using immersive technologies on the basis of sustainable development. An important element of such training is teamwork, which is a simulator of the typical work of modern IT companies.

The discipline “Fundamentals of entrepreneurship and business planning in IT” was developed taking into account the provisions of the development strategy of the Lviv Polytechnic, which, in turn, is based on the goals of sustainable

development. In particular, the following goals are defined in the university's development strategy [25]: strategic goal 1: "Attract talented youth motivated to study at the university", strategic goal 2: "Create an environment favorable for study, work, and personal development." They correspond to the UN's Sustainable Development Goals: 4 – "Quality education", 12 – "Responsible consumption and production", 17 – "Partnership for sustainable development", 8 – "Decent work and economic growth".

Applying immersive technologies in the educational process, in 2024 students developed projects:

- "FizMat:) " – a mobile application that offers interactive educational materials in physics and mathematics;
- "Study&Travel" – a mobile application and a web version of the development for studying places of interest in different countries of the world;
- "Medix" – a mobile application for students of medical specialties, which allows virtual interaction with various organs of the body in order to study them;
- "Ieeeeeisty!" – a web platform and mobile application, on the basis of which users can independently develop the recipe of the desired meal and even make it by interacting with the necessary components in the application.

In addition to the above, popular project topics include reading books, translations, financial analytics, animal care, music generation, tutoring, etc. All of them contain an immersive component (RR, VR, AR, MR, XR, 360° photo and video content, 360° broadcasts). During the development of these projects, students took into account the UN's Goals of Sustainable Development, which relate to various aspects of energy and resource conservation (goals 6, 7, 11–15), human health and well-being (goals 1–3, 8, 10, 16, 17), development of industry, innovation, and infrastructure (goals 9, 17).

As part of the grant agreement under the EU program "ERASMUS+" at the Lviv Polytechnic, students are invited to attend the optional courses "Economics of sustainable development in the context of digitalization" and "Methods and models of digital support for sustainable economic development: European practices" [27]. During 2023–2024, the specified courses were chosen by students of various undergraduate majors (in general, more than 250 people/year) and master's degrees (in general, more than 100 people/year), which proves the high level of relevance of the tasks declared by the academic disciplines. The criteria for mastering knowledge by students within the specified disciplines is the level of studying the material presented by the lecturer with the use of immersive technologies. In particular, with the use of augmented reality mobile applications during the study of environmental problems and the calculation of the socio-economic effectiveness of measures to overcome them. At the same time, students conduct research in areas related to their majors.

5.2. Justification of the method and indicators for evaluating the effectiveness of implementing immersive technologies at universities

Measuring the effectiveness of implementing immersive technologies in the educational process is characterized by a high level of uncertainty, which is the biggest problem for the application of all modern methods and models for this. It is not always possible to certify the result of using immersive technology during training (sometimes it can be evaluated only for a certain time after its completion). However, after training, students who can answer questions about the ef-

fectiveness of their use of such technologies in project work are not always present. In addition, there is a problem of disagreement of experts' judgments due to the lack of necessary methods and explanations regarding the evaluation process.

Quantitative and qualitative indicators, heuristic rules, etc. should be used for a reasonable assessment of the above-mentioned processes. At the same time, during the identification of data on the basis of formal logic, there is a conflict between clear and unclear knowledge. To solve such a situation, it is advisable to use the methods of the theory of fuzzy sets, which make it possible to properly formalize various economic interactions. One of the methods of fuzzy set theory is Mamdani's method of fuzzy logic, developed for the construction of fuzzy control systems.

The situation with the assessment of the level of effectiveness of implementing immersive technologies in the educational process is characterized by a significant amount of multifaceted data. In particular, the level of digital literacy and practical skills of students and lecturers, the level of use of immersive technologies and individualization of the experience of generating author's ideas based on them, the level of student involvement and synergy of teamwork, etc. Aggregation of the specified characteristics should give an assessment of the specified situation, which will show the level of success of the use of immersive technologies in the educational process. First of all, for this, a system of indicators should be substantiated, which will characterize the identified process in various ways.

On the basis of the study of factors influencing the effectiveness of implementing immersive technologies in the educational process, taking into account the goals of sustainable development, the characteristics of the system of indicators for its evaluation were defined (Fig. 1).

Evaluation of the level of effectiveness of implementing immersive technologies should be carried out using a system of integrated indicators, which will include various aspects of the specified process. To this end, a thorough study was conducted:

- indices, parameters, indicators of leading international organizations representing analytics in the subject area (World Economic Forum (WEF), Gartner, Data & Society Research Institute, Forrester, International Data Corporation (IDC), McKinsey Global Institute (MGI), OECD and others);
- balanced systems of indicators, methods of assessing problems characterized by inaccuracy of entered data presented in the scientific literature;
- research of a practical nature, comments of specialists of companies and authorities working in the field of implementation of innovations for sustainable development;
- the authors' empirical experience in the field of methodological problem solving in relation to innovative technologies and sustainable development;
- elaborated results on the research topic obtained during the survey and consultations with students.

Therefore, for the needs of the above-mentioned assessment, two integrated indicators are proposed:

- I_1 – evaluation of the effectiveness of immersive technologies based on the principles of sustainable development, implemented by students in the educational process (dominant internal expert environment – judgment of students);
- I_2 – evaluation of the effectiveness of immersive technologies on the basis of sustainable development, implemented by lecturers in the educational process (external expert environment dominates – judgment of lecturers).

Characteristics of the system of indicators for evaluating the level of effectiveness of implementing immersive technologies on the basis of sustainable development at universities	
The purpose of forming a system of indicators	To assess the effectiveness of implementing immersive technologies in the educational process, taking into account the goals of sustainable development
Evaluation object	Processes of implementation of immersive technologies in education based on the ideology of sustainability
The essence of the evaluation process	Measuring the level of effectiveness of implementing immersive technologies in the educational process, taking into account the goals of sustainable development
Principles of the system	Systematicity, reliability, comprehensiveness, validity
Evaluation subjects	Universities and other educational institutions
Evaluation interval	Annual
Context unit	Various aspects of data on the implementation of immersive technologies in the educational process on the basis of sustainable development
The context of interpretation of processes of implementation of immersive technologies	Two-dimensional: experts of internal and external environments
Types of evaluation indicators	Integrated
Type of coordination of evaluation indicators	System of integrated indicators
Other characteristics of the system of evaluation indicators	Scalability of results
Specificity of the assessment environment	Evaluation of the level of effectiveness of immersive technologies: as methods of teaching and application by students in their educational projects
The nature of the development of the system of evaluation indicators	Dynamic, extractive
Data sources for the evaluation system	Expert assessments of internal and external environments, statistical assessments, data from analytical sources of the subject area
The nature of formalization of knowledge in the system	Indeterminacy, indeterminacy, ambiguity

Fig. 1. Characteristics of the system of indicators for evaluating the level of effectiveness of implementing immersive technologies on the basis of sustainable development at universities

The indicator of the effectiveness of immersive technologies on the basis of sustainable development, implemented by students in the educational process (I_1), is intended to represent the level of understanding and effectiveness of the use of immersive technologies in student educational projects. This will make it possible to analyze the state of spread of the ideology of sustainable development in the minds of students. The indicator is determined by their expert evaluations of the course, the results of which are evaluated, and contains level indicators:

- assimilation of knowledge by students in the subject area, using immersive technologies (I_{11});
- development of practical skills (use of immersive technologies in project work) (I_{12});
- increasing the digital education of students (I_{13});
- individualization of experience and the possibility of generating author's ideas based on immersive technologies (I_{15});
- obtaining (expanding) the latest skills in related fields (I_{15});
- increasing the student's involvement in the educational process (I_{16});
- design efficiency: accuracy, realism of simulations, reduction of errors (I_{17});
- teamwork synergies (I_{18});
- readiness for market commercialization of student developments (I_{19});
- compliance of the project work with the development strategy of the university (according to the goals of sustainable development) (I_{110}).

The indicator of the effectiveness of immersive technologies based on the principles of sustainable development, implemented by lecturers in the educational process (I_2), is intended to represent the level of effectiveness and feasibility of using immersive technologies by lecturers in the process of teaching educational material. The indicator is determined

by their expert evaluations of the course and other experts in the subject area, contains level indicators:

- increasing the involvement of students by the lecturer, the effectiveness of distance learning (I_{21});
- improvement of students' spatial thinking (I_{22});
- reduction of costs for educational materials, automation of the educational process (I_{23});
- visualization, audio experience, quality of material presentation, etc. (I_{24});
- research interactivity (I_{25});
- feedback depth (I_{26});
- stability of the educational process based on immersive technologies (I_{27});
- digital education of lecturers (I_{28});
- compliance of the project work with the university's development strategy (according to the goals of sustainable development) (I_{29}).

Performance indicators should be determined based on data on the past and current state of the subject's use of immersive technologies in the educational process, based on the "High", "Medium", "Low" ratings. Together, integrated indicators (I_1) and (I_2) form an indicator of the effectiveness of implementing immersive technologies in the educational process on the basis of sustainable development (I). The indicators are coordinated into system (1), where $f(I_1)$ and $f(I_2)$ are functions of the first order, and $f(I)$ is of the second order, respectively:

$$\begin{cases} f(I) = f((I_1); f(I_2)), \\ f(I_1) = f\left((I_{11}); f(I_{12}); (I_{13}); f(I_{14}); (I_{15}); \right. \\ \left. f(I_{16}); (I_{17}); f(I_{18}); (I_{19}); f(I_{10})\right), \\ f(I_2) = f\left((I_{21}); f(I_{22}); (I_{23}); f(I_{24}); \right. \\ \left. (I_{25}); f(I_{26}); (I_{27}); f(I_{28}); (I_{29})\right). \end{cases} \quad (1)$$

Thus, a system of indicators was built for evaluating the level of effectiveness of immersive technologies implemented in the educational process of universities on the basis of sustainable development. It is the basis for understanding the expediency and effectiveness of using immersive technologies in the educational process, the depth of the introduction of the ideology of sustainable development.

5.3. Modeling the interaction of indicators in the system for evaluating the effectiveness of implementing immersive technologies at the university

In order to apply methods from the theory of fuzzy sets, it is advisable to interpret the elements of system (1) in accordance with the conceptual and categorical apparatus of this theory. Thus:

- I – the relative indicator of the level of effectiveness of implementing immersive technologies in the educational process, taking into account the provisions of sustainable development (the top of the hierarchy), will be determined based on the limits: $[I_1; I_2]$;

- I_1, I_2 – integrated indicators (influence factors) of the effectiveness of immersive technologies on the basis of sustainable development, implemented by students and lecturers, respectively, thermal peaks, units;

- $I_{11}–I_{19}$; I_{110} and $I_{21}–I_{29}$ are indicators of integrated indicators (attributes of influencing factors). Reductions f_I, f_{I1}, f_{I2} are carried out on the basis of logical output based on fuzzy knowledge bases.

Based on the development of fuzzy logic methods, the basis for substantiating the methodological tools of this research was formed. Therefore, a fuzzy subset of the set S is defined as a set of ordered pairs $A = \{(x, \mu_A(x)) | x \in S\}$, where $\mu_A(x)$ is a membership function that takes values in the interval $[0, 1]$. This function determines the degree to which an element x belongs to a subset A . A value of “0” means that the element does not belong to the set, and “1” means full membership. For elements $x \in S$, $\mu_A(x)$ can take any value from 0 to 1, while there is at least one element with maximal membership, that is, $\sup_{x \in S} [\mu_A(x)] = 1$. The $\mu_A(x)$ function is used to transform linguistic variables into a mathematical form, which makes it possible to use fuzzy logic methods to justify decisions. The terms are given in Table 1.

Applying the values of the terms given in Table 2, a rule base was formed for the attributes of the effectiveness of immersive technologies on the basis of sustain-

able development, implemented by lecturers and students in the educational process. In some scenarios, the weight of the rule $[0...1]$ is used in order to take into account the level of its significance. Rule bases and features are entered into the algorithm of the Mamdani model (a component of the Fuzzy Logic Toolbox in the MATLAB R2024a software package), Fig. 2. For the selected model, the trimf function for the distribution of the input values of the features is applied. Defuzzification was carried out using the center of gravity method.

Modeling of indicators I_1 and I_2 made it possible to obtain a number of visualizations, examples of which are given in Fig. 4, *a, b*.

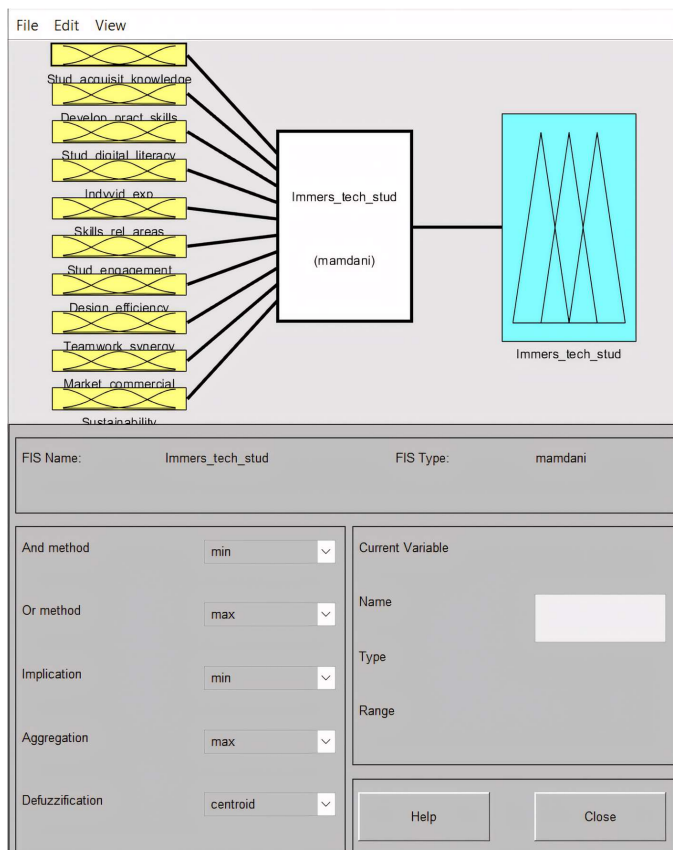


Fig. 2. The Mamdani model for determining the efficiency index of immersive technologies based on the principles of sustainable development, implemented by students in the educational process (I_1)

Table 1

Values of the terms of integrated indicators for the implementation of immersive technologies and the indicators they contain

Indicator (attribute)	Attribute term
Indicator of the effectiveness of immersive technologies based on sustainable development, implemented by students in the educational process (I_1)	(<i>Immers_tech_stud</i>): low score (Low, L) – $[0; 15; 30]$; tolerable (Tolerable, T) – $[30; 40; 50]$; admissible (Admissible, A) – $[50; 60; 70]$; high (High, H) – $[70; 85; 100]$
$I_{11}; I_{12}; I_{13}; I_{14}; I_{15}; I_{16}; I_{17}; I_{18}; I_{19}; I_{110}$	Low score (Low, L) – $[0; 15; 30]$; middle (Middle, M) – $[30; 50; 70]$; high (High, H) – $[70; 85; 100]$
An indicator of the effectiveness of immersive technologies based on sustainable development, implemented by lecturers in the educational process (I_2)	(<i>Immers_tech_teach</i>): Low score (Low, L) – $[0; 15; 30]$; tolerable (Tolerable, T) – $[30; 40; 50]$; admissible (Admissible, A) – $[50; 60; 70]$; high (High, H) – $[70; 85; 100]$
$I_{21}; I_{22}; I_{23}; I_{24}; I_{25}; I_{26}; I_{27}; I_{28}; I_{29}$	Low score (Low, L) – $[0; 15; 30]$; middle (Middle, M) – $[30; 50; 70]$; high (High, H) – $[70; 85; 100]$

The resulting surfaces (Fig. 4, *a, b*) within the framework of the system testify to the degree of interaction between the features and factors $f(I_1)$ and $f(I_2)$. The membership functions of fuzzy subsets to the fuzzy set of the above-mentioned integrated indicators of the effectiveness of immersive technologies are composed so that their values are in the range [0 ... 100], which is due to the needs of further justification.

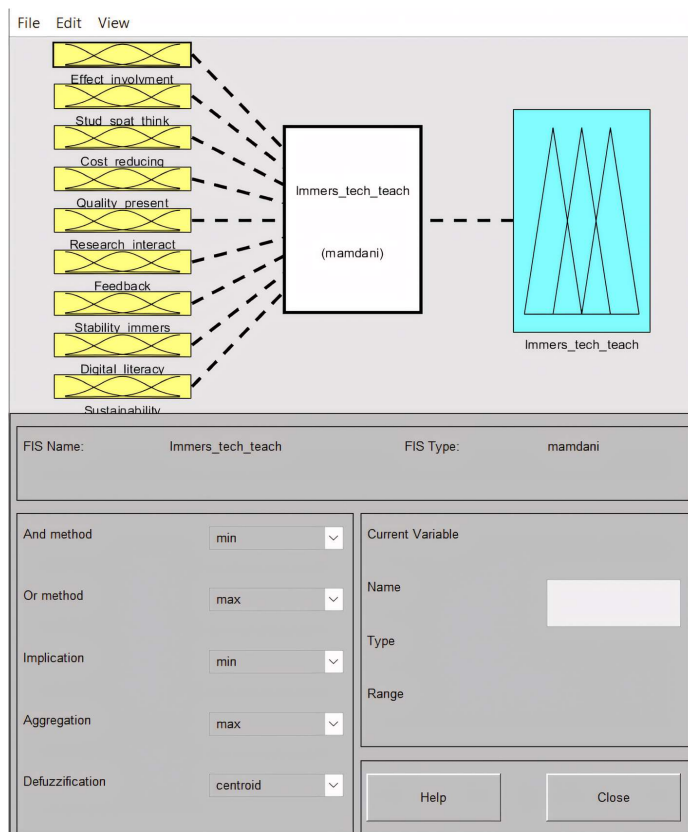


Fig. 3. The Mamdani model for determining the effectiveness of immersive technologies on the basis of sustainable development, implemented by lecturers in the educational process (I_2)

5.4. Justification of the GE/McKinsey approach for evaluating the effectiveness of implementing immersive technologies in the university

To interpret the results of evaluating the level of effectiveness of immersive technologies and justify further actions in the system of sustainable development of the university, it is advisable to use matrix approaches. For our study, the GE/McKinsey matrix (“business screen”) was chosen, which includes 9 quadrants [29] and is based on measuring the long-term attractiveness of the industry and business competitiveness. Having considered this matrix, it is obvious that by applying the principle of dividing the evaluation process into ranges, it is possible to establish the level of depth of this or that phenomenon under study. For the needs of evaluating the level of effectiveness of implementing immersive technologies in the educational process, taking into account the principles of sustainable development, the content of the existing coordinate axes should be adjusted. In particular: “Effectiveness of immersive technologies based on the principles of sustainable development implemented by students in the educational process” (X) and “Effectiveness of immersive technologies based on the principles of sustainable development implemented by lecturers in the educational process” (Y) (Fig. 5).

The relevance of such a replacement is justified by the similarity of the evaluation ranges (Table 2), the possibility of differentiating strategic measures in accordance with the current situation, etc. According to the adapted GE/McKinsey matrix, for each of the nine quadrants, ranges of values of integrated indicators [I_1 ; I_2] and, accordingly, the strategies that will fit the specific assessment situation, were implemented. Values of [I_1 ; I_2] are obtained from the Mamdani model, using MATLAB R2024a. The ranges of values used in the scale of the Mamdani model (Fig. 2, 3) are commensurate with the values of the coordinate axes of the GE/McKinsey matrix.

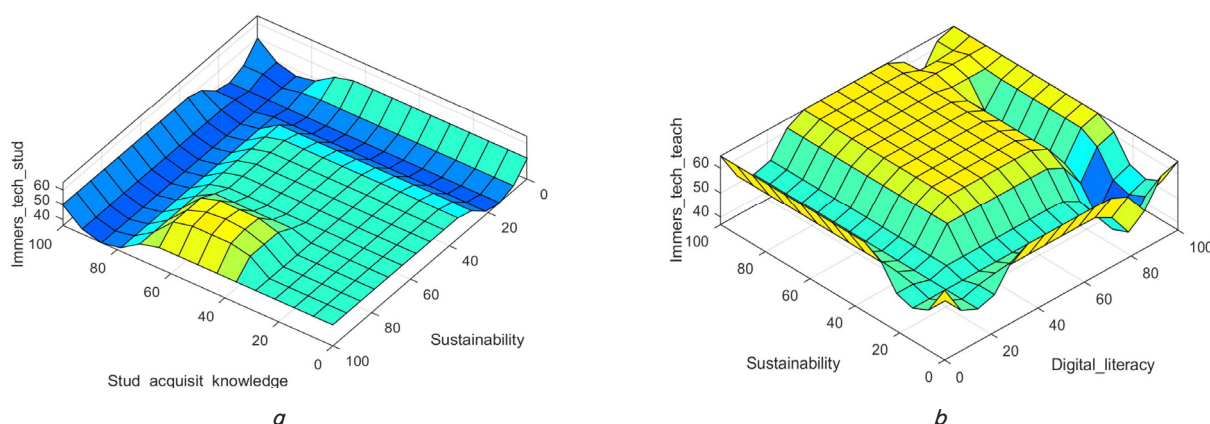


Fig. 4. Visualization of the results of modeling the dependence of indicators: *a* – the dependence of indicators of the level of assimilation of knowledge by students in the subject area, with the use of immersive technologies (I_{11}) and the compliance of the project work of students with the university development strategy (I_{10}), their influence on the effectiveness of immersive technologies on the principles of sustainable development, implemented by students in the educational process (I_1); *b* – the dependence of indicators of the level of digital education of lecturers (I_{28}) and the compliance of project work with the university development strategy (I_{29}), their influence on the effectiveness of immersive technologies on the principles of sustainable development, implemented by lecturers in the educational process (I_2)

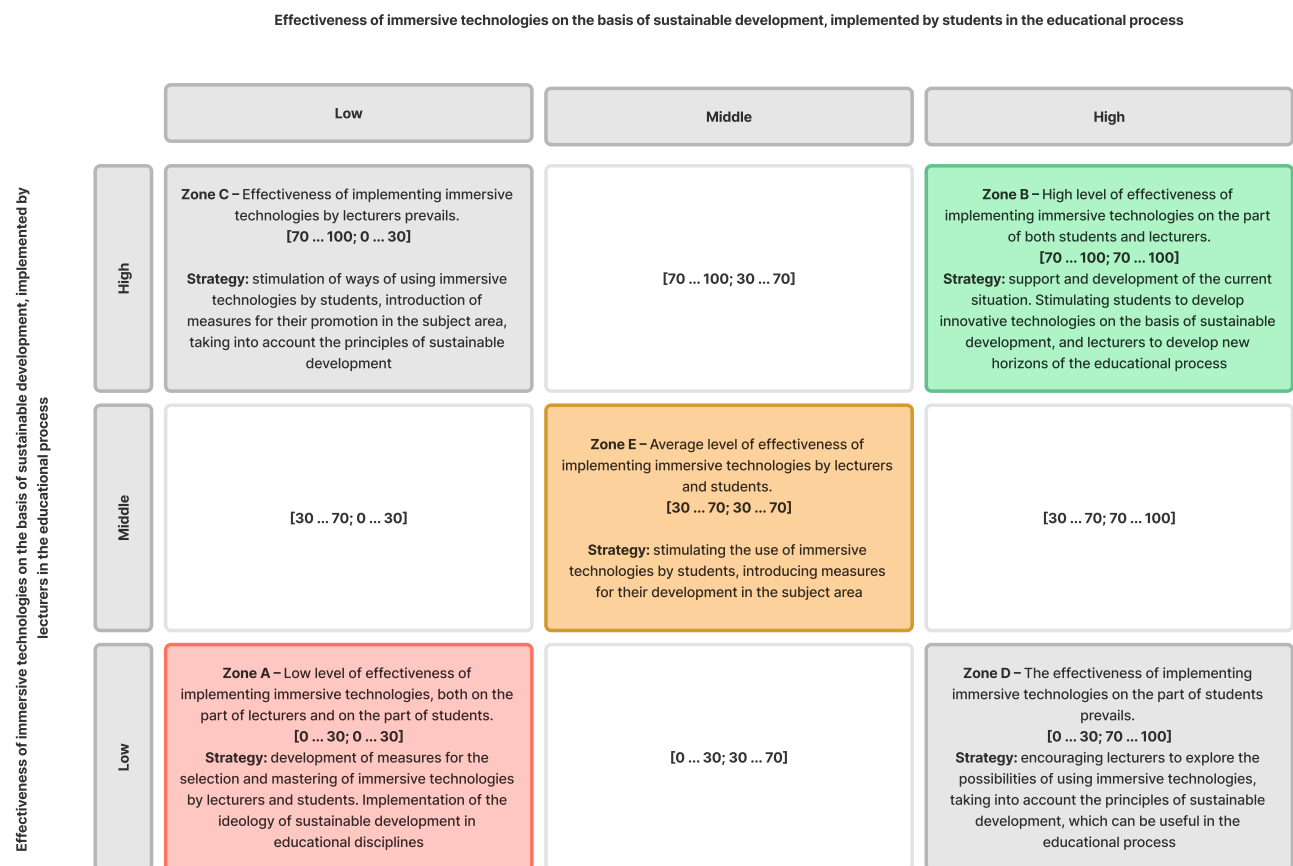


Fig. 5. The GE/McKinsey matrix, adapted for the needs of determining the level of implementation of immersive technologies on the basis of sustainable development in the educational process and proposed strategies for the development of disciplines

The work carried out proves that it is mostly possible to clearly establish the level of effectiveness of implementing immersive technologies in the educational process and to determine the strategy for the development of the discipline. However, sometimes you can find yourself in the “transitional quadrant” (shown in white in Fig. 5). This means that the level of students and lecturers in the use of immersive technologies is characterized by a certain inconsistency. Therefore, there is a risk that the materials prepared by the lecturers may not be mastered by the students to the required extent. Then it is necessary to analyze the trend of the progression of this situation, to consider the studied integrated indicators in terms of their indicators.

5.5. Verification of the method for evaluating the effectiveness of implementing immersive technologies in the university

Evaluation of the level of effectiveness of implementing immersive technologies in the educational process was carried out on the basis of the methodical toolkit proposed above and MATLAB 2024a. To do this, the integrated indicators of the effectiveness of immersive technologies implemented by students and lecturers were studied on the example of a number of disciplines according to their indicators (I_{11} – I_{19} ; I_{110} and I_{21} – I_{29}). In particular, “Fundamentals of entrepreneurship and business planning in IT”, “Economics of sustainable development in the context of digitalization”, and “Methods and models of digital support for sustainable development of the economy: European practices”. After

that, expert evaluation was applied in the MATLAB 2024a “rules” environment and expert opinions were agreed upon.

The obtained estimates were interpreted according to the adapted GE/McKinsey matrix (Fig. 5). The results are given in Table 2.

During the evaluation of the level of effectiveness of implementing immersive technologies in the discipline “Fundamentals of entrepreneurship and business planning in IT”, we observe: the efficiency indicator of students is quite high – 83.5 units, as well as the indicator of lecturers – 91.2 units. This proves, on the one hand, the significant effectiveness of lecturer training, and on the other hand, the high level of students’ understanding of the tasks of their project work. It is known from practice that more than 80 % of project team members were students from technical specialties who were familiar with the basics of immersiveness. Teamwork contributed to successful collaboration and knowledge exchange between students from technical and non-technical specialties during the course. In addition, students were asked to choose the type of immersive technology that would be most suitable for their developments. As a result, students generated projects of innovative products, almost ready for market commercialization.

In the situation with the discipline “Economics of sustainable development in the context of digitalization”, the desired indicator in the student environment was 61.5 units, in the teaching environment – 78.4 units. Compared to the previous one, this group of students did not have the opportunity to choose immersive technologies for work. The idea

of the course was to apply the technologies proposed by the lecturer, study the state of a certain environmental phenomenon, develop measures for its improvement and determine their socio-economic efficiency.

Development, should be written in more detail in the working materials of the studied disciplines. This will increase the effectiveness of the correlation of student projects with the goals of sustainable development and, accordingly, will

increase the level of effectiveness of implementing immersive technologies on the basis of sustainability.

The use of immersive technologies in education is characterized by both advantages and disadvantages. For example, collection of personal data under conditions of inadequate protection may pose a risk to privacy. This important aspect should always be in the field of view of students and lecturers during the implementation of immersive technologies in the initial process.

The justification of the choice of the method for assessing the level of effectiveness in implementing immersive technologies on the

Indicators of the level of effectiveness of implementing immersive technologies on the basis of sustainable development in the educational process at the Lviv Polytechnic

Study disciplines, number of students	Integrated performance indicators of implemented immersive technologies, units		Coordinates of the level of effectiveness of the implementation of immersive technologies on the adapted GE/McKinsey matrix, $[I_1; I_2]$, strategy for the development of educational discipline
	Students (I_1)	Lecturers (I_2)	
“Fundamentals of entrepreneurship and business planning in IT”, 2nd year (over 500 people)	85.3	91.2	[85.3; 91.2] – Strategy of support and development, encouraging students to develop innovations on the basis of sustainability, and teachers to develop new horizons of the educational process
Optional course “Economics of sustainable development in the context of digitalization”, 3 rd and 5 th courses (over 150 bachelors and 56 masters)	61.5	78.4	[61.5; 78.4] – Transition quadrant
Optional course “Methods and models of digital support for sustainable economic development: European practices” 3, 5 courses (over 100 bachelors and 48 masters)	69.8	89.7	[69.8; 89.7] – Transition quadrant

A similar situation with the assessment of immersiveness in the discipline “Methods and models of digital support for sustainable development of the economy: European practices”: the rate of students – 69.8 units, lecturers – 82.7 units. According to the adapted GE/McKinsey matrix, their evaluation results indicate the transition quadrant. The situation is due to the fact that lecturers working on the preparation of optional courses within the framework of the above-mentioned EU program [27] make corrections to them (this is the first year of teaching the course). Over time, the discrepancy between lecturers and students will gradually decrease.

basis of sustainable development showed a significant degree of uncertainty of the studied situation. It is obvious that it is not easy to prove the result of using immersive technology during training. For the most part, this can be implemented only after it is completed. However, the disadvantage is that in this case there will not always be experts present (for example, students) who can give answers to questions about the effectiveness of using immersive technologies in their work. There is also the problem of disagreement of experts’ judgments due to the lack of methodical tools for evaluation. Then you should use quantitative and qualitative indicators, heuristic rules, etc. During the research, it was proved that it is expedient to use the method of fuzzy logic from the theory of fuzzy sets, which makes it possible to create logical systems operating with fuzzy values.

The situation with the evaluation of the level of effectiveness of implementing immersive technologies on the basis of sustainable development in the educational process is determined by a significant number of multifaceted data that require aggregation for evaluation purposes. To this end, a system of indicators for evaluating the level of effectiveness of implementing immersive technologies on the basis of sustainable development (1) has been developed, based on the described characteristics of such a system (Fig. 1). The work uses the approaches of leading international organizations that highlight the analytics of the subject area, presented in the scientific literature balanced indicator systems, research of a practical nature, comments of specialists of companies and bodies. The authors’ empirical experience and the results of discussing the specified problems with students are applied. Based on this, integrated indicators for evaluating the effectiveness of immersive technologies on the basis of sustainable development, implemented by students and lecturers in the educational process, are proposed. We formed values for the terms of integrated indicators and the indicators they contain (Table 1).

6. Discussion of results based on the development of methodological tools for evaluating the effectiveness of implementing immersive technologies at universities

Immersive technologies, gaining popularity every year, are implemented in one way or another in almost all educational programs of the university. Because of this, the best option for their use are disciplines that are determined by an interdisciplinary approach and unite students of different specialties, contain tasks with the use of immersive technologies on examples of specific projects. The value of interdisciplinarity in such a context was proved in works [6, 8, 9]. Therefore, “Fundamentals of entrepreneurship and business planning in IT”, “Economics of sustainable development in the context of digitalization”, “Methods and models of digital support for sustainable development of the economy: European practices” were chosen from the array of disciplines at the Lviv Polytechnic. This made it possible to obtain relevant data and substantiate the methodological toolkit for evaluating processes on the topic of research.

During the conducted research work, it was found that certain provisions of the university’s development strategy [25], which correspond to the UN’s Goals of Sustainable

On the one hand, the devised indicators will make it possible to analyze the state of spread of the ideology of sustainable development in the minds of students and lecturers, the ability of students to generate innovations based on the goals of sustainable development. On the other hand, the research revealed a number of limitations for this indicator system, namely:

- it is obvious that not all proposed indicators of integrated indicators can be applied to all evaluation situations. Each analyzed situation will be determined by its own specificity, which is determined by the peculiarities of the educational activities of various universities, their development strategies, the traditions of the formation of educational programs and the recruitment of students, the educational systems of countries, etc.). This will require corrections to be made to our methodology, precisely at the stage of forming evaluation indicators. Therefore, the results of the study proved that hypothesis 1, which indicated the universality of the application of the developed methodological toolkit, is not fully true: the approach to the formation of indicators and their main part remains constant, but the content of individual indicators (according to indicators) can be adjusted, in accordance with the university's requests ;

- the risk for the proposed integrated indicators is the rapid development of innovative technologies in the world as a whole, which also affects the development of immersive technologies. Therefore, the possibilities of their application should be periodically reviewed so that teaching at the university corresponds to innovative progress.

Modeling the interaction of indicators in the system for evaluating the level of effectiveness of implementing immersive technologies on the basis of sustainable development made it possible to form a basis for substantiating the methodological tools of this study. To this end, the Fuzzy Logic Toolbox component in the MATLAB R2024a software package was used. The Mamdani model for determining the level of effectiveness of immersive technologies on the basis of sustainable development, implemented by students (Fig. 2, 4, *a*) and lecturers (Fig. 3, 4, *b*) in the educational process, proved the effectiveness of its use. Unlike known ones, the proposed system is flexible, intuitive, and contains all the necessary evaluation elements that can be adjusted if necessary. Therefore, hypotheses 2 and 3, in which it was stated that the methodological toolkit for economic evaluation of the level of effectiveness of implementing immersive technologies on the basis of sustainable development in the educational process is suitable for use by both lecturers (hypothesis 2) and students (hypothesis 3), are confirmed. However, even with the successful technical use of this software product, sometimes there is a drawback caused by the subjectivity of expert judgments.

The rationale for using the GE/McKinsey matrix approach for the needs of assessing the level of effectiveness of implementing immersive technologies on the basis of sustainable development (Fig. 5) is justified from several points of view. First of all, the specified matrix is a flexible management tool that allows one to structure the values previously obtained in the MATLAB R2024a software package. Without the use of such matrix approaches, their place and role in the educational process, in particular on the basis of sustainable development, is not clear from the obtained values. Unlike existing ones, the matrix makes it possible not only to determine strategies for the implementation of immersive technologies on the basis of sustainable development but also

to consider the situations of “transitional” quadrants when the level of students and lecturers in the use of such technologies is characterized by a certain inconsistency. Then it is necessary to study trends in the development of situations, analyze integrated indicators in terms of indicators, and make appropriate decisions.

Verification of the method for assessing the level of effectiveness of implementing immersive technologies by students and lecturers, based on the principles of sustainable development, in the educational process of the university (on the example of the Lviv Polytechnic University) showed the following results regarding the studied disciplines (Table 2):

- “Fundamentals of entrepreneurship and business planning in IT”: the students' efficiency index is quite high, 83.5 units, as well as the lecturers' index – 91.2 units. In this case, it is recommended to maintain and develop the current approach to learning, gradually expanding the range of types of immersive technologies;

- optional courses: “Economics of sustainable development in the context of digitalization”: the indicator in the student environment was 61.5 units, in the teaching environment – 78.4 units. “Methods and models of digital support for the sustainable development of the economy: European practices”: the rate of students – 69.8 units, lecturers – 82.7 units. A deeper analysis of the obtained results proved that these two disciplines are read for the first time for students, therefore, over time, the lag between the values of student and lecturer indicators will decrease.

In contrast to current approaches, it is with the help of the adapted GE/McKinsey matrix that it is possible to differentiate indicators of the level of effectiveness of implementing immersive technologies with a high degree of detail. This will contribute to a detailed assessment of the specified processes at universities, and, accordingly, to the development of strategic and tactical actions for the promotion of immersive technologies in education on the basis of sustainable development.

The prospects for the development of this study are to improve the management of the system of sustainable development of the university, taking into account:

- introduction of new teaching methods (for example, use of simulation environments during training);
- ensuring inclusiveness and accessibility of education (in particular, special interactive learning environments can be created for students with physical disabilities);
- dissemination of digital culture during the educational process.

Systems of sustainable development of universities are based on their development strategies. Immersive technologies are an important element of such strategies and, accordingly, one of the ways to achieve the goals of sustainable development. Therefore, the results of this study could be useful to the management and lecturers at universities to understand the implementation and promotion of immersive technologies in the educational process; to the authorities in the subject area – for consideration in the strategies of innovative progress of the region; analytical organizations – to supplement analytical reports, analysis of technology development on the basis of sustainable development.

The prospects for the development of this study are to improve the management of the system of sustainable development of the university, taking into account:

- introduction of new teaching methods (for example, use of simulation environments during training);

- ensuring inclusiveness and accessibility of education (in particular, special interactive learning environments can be created for students with physical disabilities);
- dissemination of digital culture during the educational process.

7. Conclusions

1. Development of practical experience in the implementation of immersive technologies on the basis of sustainable development in the educational process at the Lviv Polytechnic contributed to the consideration of a whole array of educational programs of the university. Among the considered educational disciplines, those aimed at students of various specialties and years of study, characterized by an interdisciplinary approach, were selected. In particular: “Fundamentals of entrepreneurship and business planning in IT”, optional courses: “Economics of sustainable development in the context of digitalization”, “Methods and models of digital support for sustainable development of the economy: European practices”.
2. The choice of the method for evaluating the level of effectiveness of implementing immersive technologies on the basis of sustainable development is justified on the basis of the application of fuzzy logic (Mamdani method) from the theory of fuzzy sets, which makes it possible to properly formalize various economic interactions, to create logical systems that operate with fuzzy values.
- On the basis of our study of factors affecting the effectiveness of implementing immersive technologies in the educational process, a system of its evaluation, which consists of integrated indicators that highlight this process in various aspects, has been substantiated. Two integrated indicators are proposed: evaluation of the effectiveness of immersive technologies implemented by students in the educational process and evaluation of the effectiveness of immersive technologies implemented by lecturers in the educational process.
3. Based on the development of fuzzy logic methods, the interaction of indicators in the system of evaluating the level of effectiveness of implementing immersive technologies on the basis of sustainable development is simulated. To this end, the Fuzzy Logic Toolbox component from the MATLAB R2024a software package was used. The Mamdani model for determining the desired indicator of the level of efficiency proved the effectiveness of its use. Unlike known ones, this approach is more flexible, and all evaluation elements can be adjusted if necessary.
4. The GE/McKinsey matrix approach was adapted for the needs of assessing the level of effectiveness of implementing immersive technologies on the basis of sustainable

development. The adapted GE/McKinsey matrix contains coordinate axes: “Effectiveness of immersive technologies implemented by students in the educational process” (*X*) and “Effectiveness of immersive technologies implemented by lecturers in the educational process” (*Y*). According to the GE/McKinsey matrix, value ranges [*I*₁; *I*₂] (they are obtained from the Mamdani model, using MATLAB R2024a) and, accordingly, the strategies that will correspond to the specific evaluation situation, were implemented.

5. Verification of the method for assessing the level of effectiveness of implementing immersive technologies on the basis of sustainable development in the educational process at the Lviv Polytechnic) showed the following results. In the discipline “Fundamentals of entrepreneurship and business planning in IT”, the level of efficiency of students is quite high, it is 83.5 units, as well as the indicator of lecturers – 91.2 units. This proves, on the one hand, the significant productivity of lecturer training, and on the other hand, the high level of students’ understanding of the tasks of their project work. For the discipline “Economics of sustainable development in the context of digitalization”, the indicator in the student environment was 61.5 units, in the teaching environment – 78.4 units. For the discipline “Methods and models of digital support for sustainable development of the economy: European practices”: 69.8 units and 82.7 units, respectively. Therefore, according to the adapted GE/McKinsey matrix, the evaluation results indicate the transition quadrant.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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