DOI: 10.37943/17CCXJ5272

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USING STRUCTURAL EQUATION MODELING METHODS TO ASSESS THE UNIVERSITY'S DIGITAL ECOSYSTEM

Abstract: This paper explores the construction of a model for evaluating the digital ecosystem within a university, with a focus on identifying key factors influencing satisfaction with the implementation of new digital processes in the educational environment. The study employs mathematical methods, specifically factor analysis, to gauge the impact of these digital processes on the overall educational landscape. A questionnaire was designed to collect relevant data, and structural equation modeling, utilizing the asymptotically distribution-free estimation method with Grammian in STATISTICA software, was employed for survey result processing. The proposed model aims to provide insights into the dynamics of a university's digital ecosystem, offering a systematic approach to assess satisfaction levels and comprehend the implications of integrating novel digital processes within the educational framework. Mathematical methods, including factor analysis, add a quantitative dimension to the evaluation process, enabling a comprehensive understanding of the relationships between various factors. The study's methodology ensures a rigorous and systematic analysis of survey data, enhancing the reliability of the findings. The developed model and methodology contribute to advancing our understanding of the digitalization of university environments, providing valuable tools for decision-makers in shaping effective strategies for integrating digital processes in education. The study conducted a survey with 350 participants, including university staff and students. A questionnaire with 17 questions, both open and closed-ended, was developed to collect data. The authors employed structural equation modeling, specifically the asymptotically distribution-free estimation method, for data processing. The study's a posteriori model illustrates the structure of interaction factors influencing satisfaction with the university's digital ecosystem.

Keywords: digital transformation; digital ecosystem; mathematical statistics; structural equations; structural equation model; latent exogenous and endogenous variables; path diagram; asymptotically distribution-free estimation using Grammian (ADF).

Introduction

Increasing the efficiency of modern universities and their digital transformation is becoming one of the most pressing tasks of higher education. To understand how the digital transformation of a university should occur, we studied the Gartner Hype Cycle 2023 study, which identifies 25 new digital technologies that are promising for the coming decades. These technologies offer opportunities for sustainable differentiation and increased competitiveness of businesses [1], we tried to adapt Gartner's approach for universities. The developed digital ecosystem (DES) of the university facilitates access to educational resources, improves communication and collaboration, increases the efficiency of managing the educational process and ensures data security. DES helps create a conducive environment for learning and research, contributing to the development of the university and its community. The digital ecosystem refers to digital transformation in relation to the digital environment of the university. Many researchers believe that one of the important tools for transforming universities is the formation of a digital ecosystem. At the same time, the authors present as elements of a digital ecosystem: the digital environment, interaction participants (stakeholders), a system of connections between participants; participant involvement; university functions reflected in numbers; idea and values regarding digital technologies; digital productivity and adequacy [2].

In work [3], the authors define a digital ecosystem as a digital environment of products, services, services and business processes, as well as the interaction of subjects, based on mutually beneficial relationships and existing as a single whole. The authors in [4] describe a digital system as a set of interconnected and complementary digital services united by a technological platform.

Since any transformation of the digital ecosystem is aimed at improving the quality of the digital services provided. Kazakh and foreign scientists are engaged in such research. Kazakh researchers [5] proposed a conceptual model of university management using modern digital technologies and developed an integrated approach to solving the problem of Digitalization of education in the Republic of Kazakhstan. The article [6] proposes algorithms for the use of digital educational technologies based on the following educational goals: the ability to think outside the box, take a creative approach to solving problems, and develop logic and intelligence. Many researchers, when designing and developing a digital ecosystem, pay attention to the development of an effective system for managing and supporting interaction with users (usability), for example, as presented in [7] for the interaction of students with IoT. Researchers are also considering new business models in education; work [8] presents a new business model: Education as a Service (EaaS), based on Industry 4.0/Industrial Internet technologies and especially on recent advances in cloud computing.

In addition to the proposed models of digital transformation, many researchers analyze or evaluate the digital transformation of the educational environment using surveys and their statistical processing. For such analysis, the 8D methodology known in marketing or the quality problem solving process is used. Many sources discuss the topic of implementing a search for factors influencing quality in various fields of activity. The authors in [9] use methods in order of preference by similarity to the ideal solution (TOPSIS) technology to rank and evaluate factors of teachers' readiness to implement online learning technologies. This study tested the Cochran-Mantel-Haenszel conditional independence of the Pearson Chi-square test to assess teachers' success in online teaching. The study [10] analyzed questionnaires regarding the assessment of the effect of blended learning from the point of view of the concept of the interdisciplinary STEAM education model (science, technology, engineering, arts and mathematics education). The effects of online-offline learning environment, online learning resources, and offline learning process in blended learning on students' learning satisfaction were measured using structural equation model (SEM).

Thus, establishing feedback from users based on collecting their opinions, reviews and comments about all components and structural elements of the educational process of universities is the most important aspect for determining the levels of satisfaction and competitiveness of the university's central economic system. Our study examines the problems of developing the digital ecosystem of Kazakhstani universities based on an assessment of digital transformation from the point of view of the end user: student, employee and teacher. Objectives of the study: creating a questionnaire based on which it is possible to identify factors of satisfaction with the implementation of new digital processes in the educational environment of universities; assessing the impact of new digital processes in the educational environment using mathematical methods of factor analysis. According to the instructions of the Ministry of Science and Higher Education of EKTU named after. D. Serikbayev entered into the pilot project "Digital University", which has been implemented since 2023.

Increasing the efficiency of modern universities is becoming one of the most pressing tasks of higher education. The digital transformation of higher education has been actively discussed over the past decades. Theoretical and practical problems of digital transformation of higher education, the integration of digital technologies into the educational space depend on various external and internal factors.

Figure 1. University digital ecosystem

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
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Digitalization of education has a practice-oriented view of the use of educational processes at the regional, national and international levels of higher education. A comprehensive look at the interaction of many factors in educational processes allows us to take a fresh look at learning in higher education. Integrating environmental, economic, social, technical and technological aspects of systems design into one specific system through forms of digitalization and automation of service processes transforms higher education systems into digital ecosystems.

A special questionnaire was developed to collect information. The questions were formulated in such a way as to assess the process of solving problems in the field of quality of digital transformation and its implementation. Therefore, to develop the questionnaire, a hypothetical model of the structure of the interaction of factors was determined, taking into account Maslow's hierarchy of needs in relation to the digital transformation of a university (Fig. 2).

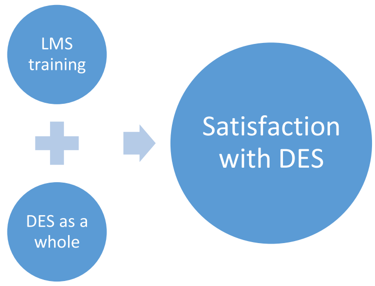

Figure 2. Interaction of factors taking into account Maslow's hierarchy of needs

When compiling the questionnaire, 17 questions were formulated, which can be used to identify the influence on two main factors: Factor 1. LMS system - as digital educational content; Factor 3. Digital ecosystem of the university as a whole with elements of digitalization of all business processes (Education: work with applicants, learning management system (LMS), management of student data and teaching staff (SIS); Science: management of all aspects of scientific research, management of scientific data (RIS); Integration: integration of data from external sources Scopus, WebOfScience, Unified Platform for Higher Education, Egov, National Educational Database, etc.; Security: logging of users in the digital environment of the university, FaceID system integrated with ACS, etc.). The questions were open (the respondent entered his own answer) and closed (the respondent was asked to choose an answer from a list) types.

Methods and Materials

Questioning is the main tool designed to identify and solve existing problems, as well as make any decisions. At the same time, when surveying, there are many variables that cannot be measured directly, therefore, the question is asked which method will allow this to be done. This article examines and analyzes collected data sets of respondents (students, faculty, staff) to assess the quality of the university's digital ecosystem [11]. The assessment of the university's digital ecosystem was considered in its entirety: organizational, methodological, technological and technical support for the educational space. During the study, the hypothesis was tested that the university's DES fully satisfies all the preferences of the subjects of the educational space; and the second alternative hypothesis that the university's DES does not satisfy (or partially satisfies) the preferences of subjects of the educational space. Thus, with the help of the study it was necessary to identify factors influencing the further development of the university's DES as a whole. Questioning is a fairly effective way of collecting and processing primary information for a certain subject area; works present the results of processing questionnaires in education and research evaluation of the work of a university [12].

Data processing with the results of the survey is carried out using mathematical methods, among which we can note the methods of factor analysis: the method of principal components, correlation analysis, the maximum likelihood method, confirmatory factor analysis, also variance and loglinear analyzes and others. The work [13] assessed patient satisfaction with the quality of medical services using the structural modeling method. The study used structural modeling using SPSS AMOS software. The structural modeling method allows you to evaluate the cause-and-effect relationships between the structures of the data under study, based on their qualitative causality, test and confirm the put forward research hypotheses, and formulate management decisions to increase patient satisfaction with medical services. Researchers from the Leuven Center for Biostatistics and Statistical Bioinformatics Katholieke Universiteit Leuven (Belgium) [14] used a pairwise modeling strategy to analyze the survey results, which uses all possible bivariate mixed models and where the conclusion follows from pseudo-likelihood theory. This approach was used to assess the effects of physical activity on psychocognitive functioning, the latter measured using a battery of questionnaires. In [15], questionnaire data were assessed using one-way analysis of variance and post-hoc t-tests. Significant differences in response accuracy were found between item wording conditions. Researchers from the Institute of Technology Bisnis Haji Agus Salim Bukittinggi, Indonesia in [16] use structural equation modeling (SEM) to determine the impact of the marketing mix and perform data processing in the Smart PLS version 3.0. Thus, to assess the satisfaction of the university's DES, it is advisable to use one of the methods of statistical data processing, in particular the method of structural equations [17].

In our study, a survey was conducted "Satisfaction of different categories of users with the digital ecosystem of the university," which included the development of a questionnaire, questionnaire survey, data processing and analysis of the results obtained.The primary information received was processed using structural equation modeling, which is one of the types of confirmatory factor analysis. In addition, structural equation modeling includes not only mathematical models and various statistical methods, but also computer algorithms. When applying the methods, one should take into account causal relationships that are a consequence of the researcher's theoretical ideas, pay attention to the quality of the data collected, and use a large sample size when processing data. Structural equation models consist of two components: the first describes the relationship between endogenous and exogenous latent variables; the second component describes the relationship between latent and analyzed variables (measurement model).

The basic equation of the latent variable model is:

$$\eta=B\eta+\Gamma\xi+\zeta \tag{1}$$

where η is a vector of endogenous latent variables; ξ is a vector of exogenous hidden variables; ζ – vector of random variables; B is the matrix of coefficients $(m\cdot m)$ for latent endogenous variables; Γ – matrix of coefficients $(m\cdot n)$ for hidden exogenous variables.

The basic equations of the measurement model are as follows:

- for exogenous variables:

$$X=\Lambda\_x\ \xi+\delta \tag{2}$$

where x and δ are column q-vectors related to observed exogenous variables and errors, respectively; Λx is the structural coefficient of the matrix $(q\cdot n)$, taking into account the influence of hidden exogenous variables on the observed ones;

- for endogenous variables:

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
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$$Y=\Lambda\_y \eta+\varepsilon \tag{3}$$

where y and ε are column p-vectors related to observed endogenous variables and errors, respectively; Λy is the structural coefficient of the matrix $(p \cdot m)$, which takes into account the influence of hidden endogenous variables on observable ones.

The fact that variable X determines variable Y is indicated by a one-way arrow in the path diagram and is given by the following structural equation:

$$Y = aX + EY \tag{4}$$

where a is the coefficient of determination, EY is the remainder term.

The fact of correlation (covariance) of variables X and Y is established as $(X,Y)=b$.

In structural modeling, the covariances (correlations) of only the independent variables are specified or estimated. The covariances of the dependent variables are calculated based on the symmetry and linearity of this function: $(aX+bY,Z) = (Z,aX+bY) = a(X,Z) + b(Y,Z)$.

The covariance of a variable with itself is variation and is a measure of its spread. In diagrams (Fig. 5), variations are indicated by a circular arrow starting and ending at the variable itself, and most often they are simply mentioned and omitted in the figure itself. Variations, like covariances and coefficients of determination, can be known in advance based on theoretical considerations or previous research, or can be estimated during model analysis. Variations of the residual terms E and D, which are independent latent constructs, are considered unknown in advance, but their coefficients of determination on the dependent variables under study are assumed to be equal to 1 to set the scale.

The structural equation modeling method has several advantages over other methods:

- object-oriented nature of modeling;
- allows you to visualize and build a number of complex systems of hypotheses of relationships, observed and latent (hidden) variables;
- the ability to operate not only with observable (explicit) variables, but also with unobservable (i.e. latent) ones.
- ability to simulate complex phenomena.
- accounting for measurement errors;
- ability to check the model for compliance with the source data.

In summary, structural equation modeling, compared to other statistical models, provides a systematic analysis of causal relationships, can simultaneously handle relationships between multiple independent and multiple dependent variables, and is more comprehensive and flexible in fitting data and testing models. The respondents of the study were 350 people, 124 of which were university staff and teachers, 226 students. The survey was conducted online, from September to November 2023.

DOI: 10.37943/17CCXJ5272

Table 1. Closed-type questions

LMS training (Factor 1)	
For teachers, students	
Question	***Answer***
1 How do you assess the accessibility and ease of use of digital resources and technologies at your university for the educational process and research? **(A1)**	- high level; - good level; - average level; - low level; - I find it difficult to answer.
2 What digital competencies should a teacher have in order to improve the effectiveness of his activities in connection with the digital ecosystem of the university? **(A2)**	- technical skills in using digital technologies; - the ability to meaningfully use digital technologies for work, study and everyday life in general in various types of activities; - the ability to critically evaluate digital technologies; - all of the above.
Digital Ecosystem (Factor 2)	
For teachers, students	
3 Which of the proposed elements, in your opinion, are mandatory for a digital university? **(A3)**	- digital educational resources; - digital environment; - digital platform.
4 Do you think digital transformation is affecting each and every part of your university's operations? **(A4)**	
5 In your opinion, should digital systems be integrated with each other to create a synergistic effect? **(A5)**	
6 Who, in your opinion, makes the greatest contribution to the formation of the university's digital ecosystem? **(A6)**	- state; - employer; - university; - student; - teacher; - partner organizations.
Satisfaction with the Central Energy System (Factor 3)	
Teacher, staff, student	
How satisfied are you with the existing digital ecosystem of the university? **(A7)**	- very pleased; - rather satisfied; - neutral attitude; - rather dissatisfied; - extremely dissatisfied.

The questionnaire contained 17 questions, including 7 closed-ended questions with five answer options (scale from 0-5 points), as well as 10 open-ended questions, with respondents' own answers. In this study, we consider processing the results of a closed-type survey only.

Structural equation modeling is a type of confirmatory factor analysis that allows you to find path coefficient values for each relationship in a path diagram (similar to factor loadings). A path diagram is a research hypothesis expressed in graphical form about the structure of the relationship between manifest and latent factors [18].

There are multiple ways to specify a model effectively, providing clarity and insight into its structure and relationships. Primarily, this can be achieved through two equivalent methods: visually, utilizing a path diagram, or through a structured system of linear multiple regression

Scientific Journal of Astana IT University
ISSN (P): 2707-9031 ISSN (E): 2707-904X
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equations along with covariance relations. Path diagrams offer a visual representation akin to flowcharts, wherein variables are depicted as nodes connected by lines denoting causal relationships. Each of these paths encapsulates a relationship between two variables: latent variables, represented by ovals, and observed (manifest) variables, represented by rectangles [19]. An explicit variable is one whose values are directly observable and measurable. A causal link between variables is illustrated by a one-way arrow, originating from the independent variable and terminating at the dependent variable. Covariance relationships, indicating the degree of association between variables, are denoted by double-sided arrows.

For instance, in Fig. Figure 2, a path diagram delineates the structural model aimed at determining “Satisfaction with the DES” [20]. This diagram serves as a visual roadmap, elucidating the intricate interplay between various factors contributing to satisfaction within the context of the DES framework. Through such comprehensive visualizations, complex models can be more readily understood and analyzed, facilitating deeper insights into the underlying dynamics and relationships at play.

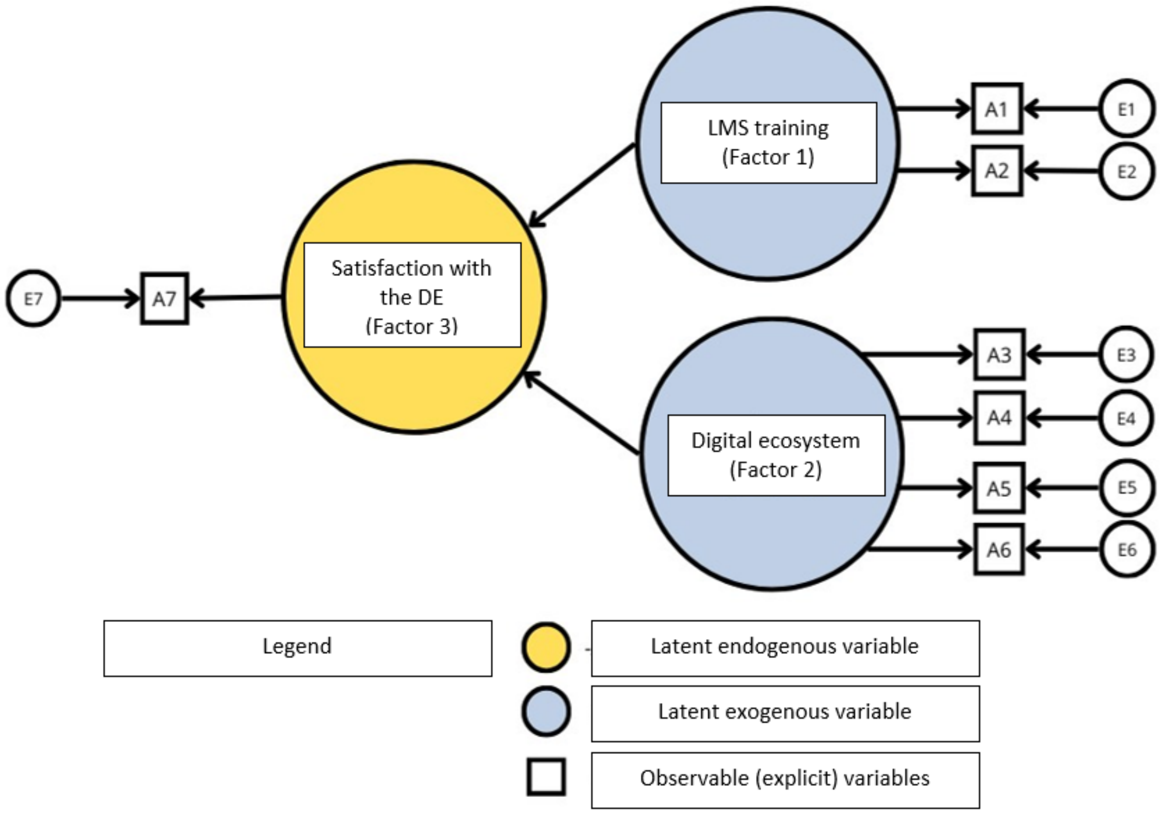

Figure 3. Path diagram of the structural model for research

The obtained survey results were processed using structural equation modeling in STATISTICA software. In the Analysis Options dialog box, the options required for data processing were selected. The Disagreement Function option suggests which disagreement function or functions will be minimized during the parameter estimation process. In our study, we used asymptotically distribution-free estimation (ADF), which does not require multivariate normality (Fig. 4).

In this case, the Gram condition (symmetry, positive semi-definiteness) is imposed on the weight matrix. Typically this matrix is also invertible. As a preliminary analysis before performing the ADF estimation, the SEPATH module performs a generalized least squares (GLS) estimation.

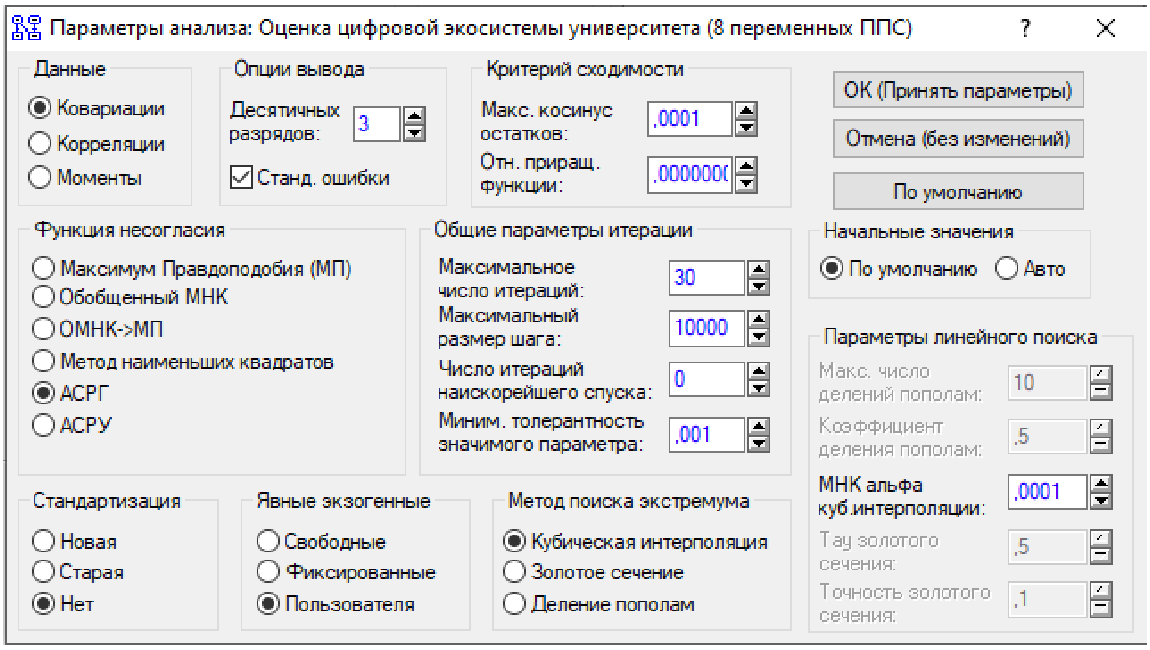

Figure 4. Analysis Parameter Dialog Box

As a result of processing, the following a posteriori model of the structure of interaction of factors (Factor 1, Factor 2, Factor 3) of satisfaction of different categories of users with the university's digital ecosystem was obtained (Fig.5).

The letters A indicate questionnaire questions – explicit variables, Factor 1-2 – latent exogenous variables, Factor 3 – latent endogenous variable and E – variances of variable residuals. Endogenous variables depend on exogenous and explicit variables. In our example, the endogenous variable Factor 3 "Satisfaction with the university central economic system" depends on two exogenous variables Factor 1, Factor 2. Exogenous variables determine the endogenous variable, but are not themselves influenced by them.

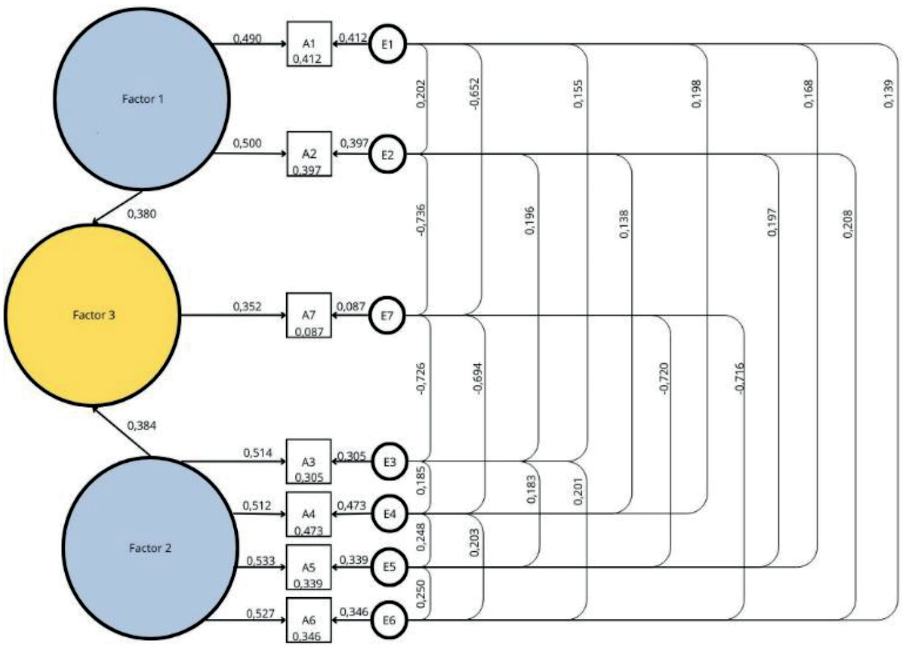

Figure 5. A posteriori model of the structure of interaction of factors of satisfaction of different categories of users with the digital ecosystem of the university

Hence, it becomes evident from the illustration in Fig. 2 that only unidirectional stochastic causal relationships are established between endogenous and exogenous variables. In our particular scenario, during the analysis phase, Factor 1 amalgamates explicit variables that exhibit strong correlations with one another. For instance, explicit variable A1 pertains to "The influence of the university's digital ecosystem on various aspects of the activities of teachers", A2 delves into "The main factors considered in the formulation and advancement of digital ecosystems within universities", and so forth.

These explicit variables are presented along a scale ranging from "0" to "5". The explicit presentation of these variables facilitates the redistribution of variances among components, yielding a straightforward and visually comprehensible structure of factors, denoted as Factor 1 and Factor 2. Consequently, as these components correlate, the coherence within each factor is enhanced, surpassing their correlation with components belonging to other factors. This mechanism enables a clearer delineation of the interrelationships among variables, enhancing the interpretability and utility of the analytical framework.

Checking the model for compliance with the original data is performed using various compliance indexes, which estimate the amount of discrepancy between the original data and what the model predicts. The model's consent indexes are shown in Table 2.

Table 2. Model goodness-of-fit indices

Index	Model goodness-of-fit index value	Recommended index values
Chi-square and degrees of freedom ($\chi 2$ and df)	193.615 21.000 df	
Root Mean Square Error of Approximation (RMSEA)	0.047	<0.05 - good
goodness-of-fit index (GFI)	0.930	>0.90or >0.9595

As can be seen from Table 1, the model goodness-of-fit indices are within acceptable limits; we can conclude that the initial data agree satisfactorily with the proposed model. At the same time, I would like to say that there are also cases of unsatisfactory agreement. In such cases, the model needs to be corrected: increasing the sample size, changing the number of slices, complicating or simplifying the model.

Thus, we can say that the scope of application of structural equation modeling methods has scientific and practical significance, and the method reveals new opportunities in assessing the effectiveness of introducing new digital processes into the educational environment of universities.

The work was carried out with the support of grant funding for scientific and (or) scientific and technical projects for 2023-2025 from the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. AP19677501 "Development of intelligent services for a smart campus with integration into the university information ecosystem").

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