Modeling the Driving Factors of Educational Technology Innovation in Indonesian Universities: A Hybrid ISM–ANP Approach

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ABSTRACT

This study aims to model the critical enablers driving technological innovation in higher education institutions in Indonesia by integrating Interpretive Structural Modeling (ISM) and Analytic Network Process (ANP). The hybrid approach provides both structural and quantitative insights into the interrelationships among eight identified enablers: policies and regulations, digital infrastructure, faculty competence, technology incentives, industry collaboration, student literacy, innovation culture, and data security. The ISM results classify policies and regulations and digital infrastructure as driving factors that form the foundational layer of innovation ecosystems. Meanwhile, faculty competence, technology incentives, and industry collaboration serve as linkage factors that bridge strategic policies and operational implementation, whereas student literacy, innovation culture, and data security emerge as dependent factors representing the system's outcomes. The ANP results reinforce the ISM structure, revealing that policies and regulations (0.215) and digital infrastructure (0.187) have the highest influence, followed by faculty competence (0.142) and industry collaboration (0.130). The combined ISM–ANP framework demonstrates that sustainable educational technology innovation requires a synergistic interaction between governance, human resources, and digital culture. The findings provide a comprehensive model that can guide universities and policymakers in formulating evidence-based digital transformation strategies within the Indonesian higher education context.

1. Introduction

Technological innovation has revolutionized nearly every sector of human activity, including higher education. In recent years, education technology (EdTech) has rapidly evolved as a response to the challenges of learning in the digital era. Universities worldwide are increasingly integrating digital platforms, artificial intelligence (AI), and adaptive learning systems to enhance teaching effectiveness and student learning experiences [1], [2]. These innovations not only enable flexible learning but also expand access for previously underserved populations [3], [4].

In Indonesia, the transformation was significantly accelerated by the COVID-19 pandemic, which forced higher education institutions to shift rapidly to remote learning. National initiatives such as Merdeka Belajar–Kampus Merdeka (MBKM) served as frameworks for institutional adaptation through widespread technology adoption [4], [5]. Digital tools such as Learning Management Systems (LMS), video conferencing applications, and online assessments have since become integral to post-pandemic academic operations.

Despite this progress, the adoption of educational technology in Indonesian universities remains uneven. Several persistent challenges hinder comprehensive digital transformation, including disparities in digital infrastructure, low levels of technological competence among faculty and students, limited institutional budgets, and the lack of incentive mechanisms to support innovation [6], [7]. Furthermore, resistance to change and underdeveloped innovation cultures continue to limit sustainable implementation, even in institutions with adequate resources [2], [8].

Most previous studies addressing these issues have remained descriptive in nature and do not analyze the interrelationships among the enabling factors. For instance, Fatimah et al. [2] examined infrastructure readiness and data security, while Andriani and Sunarso [9] identified various EdTech enablers without investigating their structural interactions or relative importance. Similarly, Yamin and Suryadi [8] emphasized the role of industry collaboration but did not construct a systemic framework linking it with broader institutional dynamics. Consequently, there remains a methodological gap in understanding how these factors interact within a structured hierarchy, which is critical for guiding strategic decisions.

This study addresses that gap by applying a hybrid approach that combines Interpretive Structural Modeling (ISM) and Analytic Network Process (ANP). ISM is used to map the structural relationships among enablers based on expert input, while ANP determines the relative priority of each factor by incorporating feedback and interdependencies. The integration of ISM and ANP offers both qualitative and quantitative perspectives, enabling a more holistic understanding of how educational technology innovation evolves in complex institutional settings. To the best of our knowledge, this combined method has not yet been applied in studies focused on Indonesian higher education, which highlights the novelty of this research.

Accordingly, this study aims to identify and model the key enablers of educational technology innovation in Indonesian universities using an ISM–ANP framework. The results are expected to contribute theoretically by extending the methodological toolkit for EdTech research and practically by offering a structured, evidence-based model that informs strategic planning for digital transformation in higher education [10], [11].

2. Method

3.1. Research Approach

This study aims to identify and model the key drivers of technological innovation in Indonesian universities. To achieve this objective, a hybrid approach combining Interpretive Structural Modeling (ISM) and Analytic Network Process (ANP) was employed. The ISM method was used to construct a hierarchical structure of interrelated factors based on expert opinions, while the ANP method was applied to determine the relative weight and priority of each factor derived from the ISM structure.

This study involved a total of seven domain experts with professional backgrounds in digital education, higher education policy, and information systems management. The experts were selected based on two criteria: (1) a minimum of five years of experience in managing or researching educational technology implementation in universities, and (2) involvement in strategic planning or digital transformation initiatives at the institutional or national level.

The number of experts was determined with reference to methodological guidelines in ISM and ANP studies, which recommend a panel of 5–10 experts to ensure sufficient diversity of perspective while maintaining manageable synthesis of input [10], [12], [16]. During the ISM phase, the experts provided structured judgments on the contextual relationships among the identified factors, which were compiled into the Structural Self-Interaction Matrix (SSIM). In the ANP phase, their pairwise comparisons were aggregated using the geometric mean to construct a consistent supermatrix. Consistency Ratio (CR) values for each matrix were computed to ensure logical coherence; all matrices had CR < 0.10, indicating acceptable levels of consistency.

By using a multi-expert panel, this study enhances the validity and generalizability of the resulting model, ensuring that the derived structural relationships and prioritization of factors reflect a broader consensus within the academic and policy-making communities in Indonesian higher education.

The selection of the ISM–ANP hybrid approach was based on two primary considerations. First, ISM enables the identification of relationships among elements within a complex system using expert knowledge and experiential insights. Second, ANP allows for a multi-criteria decision-making analysis that accounts for feedback and dependency relationships among elements, which is particularly relevant in the multidimensional context of educational technology development.

3.2. Research Stages

The research was conducted in two main phases, as illustrated in Figure 1. The first phase employed the ISM approach to map the contextual relationships among the identified factors, while the second phase applied the ANP approach to determine the relative priority of each factor based on the hierarchical structure established through the ISM analysis.

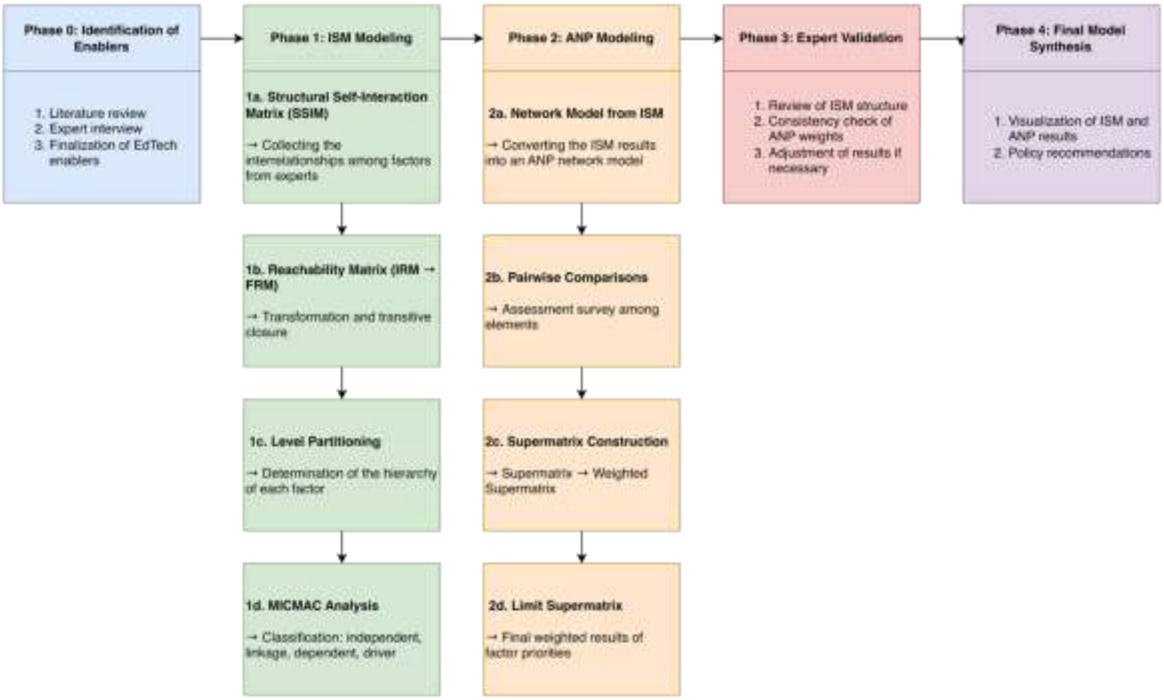

Figure 1. Research methodology flowchart of the hybrid approach using ISM and ANP

This study employed a hybrid approach integrating Interpretive Structural Modeling (ISM) and Analytic Network Process (ANP), consisting of five main phases [12]. Phase 0 involved the identification of eight key enablers of educational technology innovation through an extensive literature review and expert validation [13], [14]. Phase 1 utilized ISM to construct the hierarchical structure among factors through the processes of SSIM, IRM, FRM, level partitioning, and MICMAC analysis to classify each factor as a driver, dependent, linkage, or independent variable [15]. Phase 2 applied ANP to calculate the priority weights by building a network model derived from the ISM structure, conducting pairwise comparisons among elements, and formulating the supermatrix leading to the generation of a limit supermatrix as the final output . Phase 3 involved expert validation of both the structural model and the resulting weights to ensure consistency and contextual relevance within Indonesian higher education institutions [2]. Phase 4 synthesized the final integrated model, combining the hierarchical framework of ISM with the quantitative weights from ANP to produce strategic recommendations for the development of educational technology (EdTech) in universities [9].

3.3. Identification of Driving Factors

A total of eight driving factors of educational technology innovation were identified based on an extensive literature review and validation by higher education experts in Indonesia. These factors include policies and regulations, digital infrastructure, faculty competence, technology incentives, industry collaboration, student literacy, innovation culture, and data security (see Table 1). These factors were subsequently analyzed to determine their structural relationships and relative priorities.

3.4. Interpretive Structural Modeling (ISM)

Interpretive Structural Modeling (ISM) was employed to map the interrelationships among the identified driving factors of educational technology innovation. The ISM approach, originally developed by Warfield (1974), is widely used in complex system analysis to organize interdependent elements into a structured hierarchy. In the context of this study, ISM was applied to construct the relational structure among the eight identified EdTech innovation drivers based on expert assessments.

The first step in the ISM process involves constructing the Structural Self-Interaction Matrix (SSIM), which represents the contextual relationships among each pair of factors. Experts were asked to assess whether one factor influences another using the following notations:

- V: Factor i influences factor j
- A: Factor j influences factor i
- X: Factor i and j influence each other
- O: No relationship exists between factors i and j

The symbols in the SSIM were then converted into binary values (0 and 1) in the Initial Reachability Matrix (IRM) according to the following rules:

Table 1. Conversion Rules from SSIM to IRM in the ISM Approach (adapted from Warfield, 1974)

SSIM Value	**IRM(i,j)**	**IRM(j,i)**
V (i → j)	1	0
A (j → i)	0	1
X (i ↔ j)	1	1
O (no relation)	0	0

Each pair of factors was evaluated for its causal relationship, and the results were used to construct the Structural Self-Interaction Matrix (SSIM), which was subsequently converted into the Final Reachability Matrix (FRM). After obtaining the Initial Reachability Matrix (IRM), the next step involved developing the Final Reachability Matrix (FRM) by applying transitive closure. This process incorporates indirect relationships based on the logical rule: if factor i influences factor j, and factor j influences factor k, then factor i also influences factor k. The FRM was calculated using the following equation:

$$R = A + A^2 + A^3 + \cdots A^n \tag{1}$$

Where:

- A represents the *Initial Reachability Matrix,*
- R denotes the *Final Reachability Matrix,*
- The computation is continued iteratively until the results converge and no further changes occur in subsequent iterations (Warfield, 1974).

After obtaining the Final Reachability Matrix (FRM), level partitioning was performed to determine the hierarchical level of each factor. This process involved comparing the reachability set and antecedent set for every element. Factors whose reachability set is identical to the intersection of both sets are placed at the highest level and then removed from subsequent iterations. This procedure continues until all factors are assigned to their respective hierarchical levels.

The final step in the ISM process is the MICMAC analysis (Cross-Impact Matrix Multiplication Applied to Classification). This analysis aims to categorize the factors into four groups based on their levels of driving power and dependence:

- Autonomous, low driving power and low dependence,
- Dependent, high dependence but low driving power,
- Linkage, both driving power and dependence are high, and
- Driver, high driving power but low dependence.

This classification helps identify which factors serve as the primary drivers of educational technology innovation.

3.5. Analytic Network Process (ANP)

After establishing the structural relationships among factors through ISM, the next step was to calculate the relative priority weights of each factor using the Analytic Network Process (ANP) approach. This method, developed by Saaty (1996) as an extension of the Analytic Hierarchy Process (AHP), is designed to address decision-making problems that involve interdependence and feedback among elements within a system [16].

The initial stage of ANP involves constructing a network model based on the hierarchical structure derived from ISM. This model reflects the interconnections and dependencies among the driving factors of educational technology innovation. Once the network structure is established, a pairwise comparison process is conducted, in which experts evaluate the relative importance between pairs of elements using a 1–9 scale proposed by Saaty (2001). These pairwise comparison values are then used to construct the Supermatrix, which represents the overall influence relationships among elements within the network. The Supermatrix is formulated in the following general form [12].:

$$W = \begin{bmatrix} \omega_{11} & \omega_{12} & \cdots & \omega_{1n} \\ \omega_{21} & \omega_{22} & \cdots & \omega_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \omega_{n1} & \omega_{n2} & \cdots & \omega_{nn} \end{bmatrix} \tag{2}$$

In this equation, w_{ij}represents the influence of element j on element i. Since the initial supermatrix is unstandardized, a normalization process is applied to each column so that the total value of every column equals one. The result of this process is referred to as the Weighted Supermatrix, which accounts for cluster weights and ensures mathematical validity for subsequent calculations. The final step involves computing the Limit Supermatrix by raising the weighted supermatrix to a sufficiently large power (for example, $k \to \infty$) until the matrix values converge. This produces a stable priority vector that represents the final influence and relative importance of each factor in the network.:

$$\lim_{k \to \infty} W^k = W^* \tag{3}$$

The result of the limit supermatrix (W^***)** provides the final priority weights of each driving factor of innovation. These values serve as the basis for developing strategic recommendations related to the advancement and implementation of educational technology within Indonesian higher education institutions. To ensure the validity of the results, a consistency test was performed for each pairwise comparison matrix. Consistency was measured using the Consistency Ratio (CR)**,** and the results were considered acceptable when the CR value was less than 0.10, as recommended by Saaty (1996). This verification process ensures the reliability of expert judgments and the robustness of the computed priority weights in the ANP model [16].

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n - 1}, \mathrm{CR} = \frac{CI}{RI} \tag{3}$$

Where λ_{max} represents the maximum eigenvalue and RI denotes the random index. A Consistency Ratio (**CR**) value of less than 0.10 is considered acceptable and indicates that the pairwise comparisons are consistent [16].

3.6. Model Validity and Verification

After constructing the interrelationships among factors using ISM and obtaining the priority weights through ANP, the next stage involved model validation by domain experts. The purpose of this validation was to ensure that the modeling results aligned with empirical realities, particularly within the context of educational technology innovation in Indonesian higher education institutions. Validation was conducted through structured discussions and in-depth interviews with several experts who had previously participated in the ISM and ANP assessment process. The experts were asked to evaluate whether the hierarchical structure derived from ISM logically represented the cause-and-effect relationships and whether the contextual interpretation was appropriate. They also reviewed the consistency of the priority weights obtained from ANP to determine whether the computed values accurately reflected the urgency and importance of each factor in supporting educational technology innovation.

If any inconsistencies or mismatches were identified between the model outputs and expert perceptions, clarification discussions were held, followed by limited revisions to the structure or specific weight values. This procedure followed the approach proposed by Fatimah et al. (2021), which emphasizes the importance of continuous expert involvement to enhance the credibility and reliability of systemic modeling results. By engaging experts directly in the verification process, this phase also served as a triangulation stage to strengthen the validity of the research findings prior to the synthesis of the final model.

3.7. Phase 4 Final Model Synthesis

The final phase of the hybrid approach involved synthesizing the complete model by integrating the hierarchical structure obtained from ISM with the priority weights derived from ANP into a unified analytical framework. This final model illustrates how the eight driving factors of educational technology innovation interact hierarchically and the extent of their relative importance based on the computed weights. The hierarchical structure obtained from ISM provides insight into the relative positioning of factors-those at the lower levels act as primary drivers, while those at the upper levels represent outcomes or systemic effects. The priority weights from ANP were then used to indicate the relative influence of each factor within the overall EdTech innovation system.

The synthesized model was presented in the form of a system diagram and/or a priority table, visually depicting the logical relationships and contribution strengths of each factor. This presentation format aimed to provide a comprehensive understanding for policymakers, university administrators, and education planners in formulating higher education digital transformation strategies. For instance, if the results show that Policies and Regulations and Digital Infrastructure hold the highest weights and occupy the lowest hierarchical level, the model suggests that these two factors serve as fundamental prerequisites that must first be strengthened to support subsequent factors such as Innovation Culture or Industry Collaboration.

Thus, the final model is not merely descriptive but also prescriptive, offering actionable insights based on causal relationships and priority contributions. The synthesis results are expected to serve as a strategic foundation for developing targeted, evidence-based policies that promote sustainable educational technology innovation across Indonesian universities..

3. Results and Discussion

3.1. Results of Interpretive Structural Modeling (ISM)

Interpretive Structural Modeling (ISM) was applied to analyze the interrelationships among the driving factors of educational technology innovation that had been identified in the earlier stage. The eight factors include Policies and Regulations, Digital Infrastructure, Faculty Competence, Technology Incentives, Industry Collaboration, Student Literacy, Innovation Culture, and Data Security.

The first step in the ISM process involved constructing the Structural Self-Interaction Matrix (SSIM). The SSIM was developed based on expert evaluations of the contextual relationships between each pair of factors using the following symbols::

- V-the row factor influences the column factor,
- A- the column factor influences the row factor,
- both factors influence each other,
- O- no relationship exists between the two factors.

The SSIM derived from expert assessments is presented in Table 3 below:

Table 3. Structural Self-Interaction Matrix (SSIM) of Critical Enablers to EdTech Innovation.

No	**Factors**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	Policies and Regulations	—	V	V	V	V	V	V	V
2	Digital Infrastructure	A	—	V	V	V	V	V	V
3	Faculty Competence	A	A	—	X	V	V	V	V
4	Technology Incentives	A	A	X	—	V	X	V	V
5	Industry Collaboration	A	A	A	A	—	V	X	V
6	Student Literacy	A	A	A	X	A	—	V	X
7	Innovation Culture	A	A	A	A	X	A	—	V
8	Data Security	A	A	A	A	A	X	A	—

The next step involved converting the Structural Self-Interaction Matrix (SSIM) into the Initial Reachability Matrix (IRM) using the standard ISM conversion rules proposed by Warfield (1974). This process transformed the qualitative expert judgments represented by the symbols (V, A, X, O) into binary numerical values (0 and 1) to quantify the directional relationships among factors [17]. The resulting matrix forms the basis for determining the overall reachability of each factor within the system. The conversion results are presented in Table 4:

Table 4. Initial Reachability Matrix (IRM) of Critical Enablers to EdTech Innovation

No	**Factors**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	Policies and Regulations	1	1	1	1	1	1	1	1
2	Digital Infrastructure	0	1	1	1	1	1	1	1
3	Faculty Competence	0	0	1	1	1	1	1	1
4	Technology Incentives	0	0	1	1	1	1	1	1
5	Industry Collaboration	0	0	0	0	1	1	1	1
6	Student Literacy	0	0	0	1	0	1	1	1
7	Innovation Culture	0	0	0	0	1	0	1	1
8	Data Security	0	0	0	0	0	1	0	1

Based on the Initial Reachability Matrix (IRM), the process of transitive closure was performed to generate the Final Reachability Matrix (FRM). Subsequently, level partitioning was conducted to determine the hierarchical position of each factor within the system. The level analysis revealed that Policies and Regulations and Digital Infrastructure occupy the foundational level as driving factors, exerting the greatest influence on other elements. In contrast, Innovation Culture, Data Security, and Student Literacy are positioned at the upper levels as dependent factors, representing the outcomes of systemic interactions within the educational technology innovation framework.

After the conversion from SSIM to IRM, the next stage involved constructing the Final Reachability Matrix (FRM) by applying the transitive closure procedure. The FRM represents the complete set of both direct and indirect relationships among all factors, reflecting the full structural connectivity within the system. The results of this analysis are presented in Table 5, which displays the Final Reachability Matrix (FRM) for the eight driving factors of educational technology innovation.

Table 5. Final Reachability Matrix (FRM) of Critical Enablers to EdTech Innovation

No	**Faktor**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Driving Power**
1	Policies and Regulations	1	1	1	1	1	1	1	1	8
2	Digital Infrastructure	0	1	1	1	1	1	1	1	7
3	Faculty Competence	0	0	1	1	1	1	1	1	6
4	Technology Incentives	0	0	1	1	1	1	1	1	6
5	Industry Collaboration	0	0	0	0	1	1	1	1	5
6	Student Literacy	0	0	0	1	0	1	1	1	4
7	Innovation Culture	0	0	0	0	1	0	1	1	3
8	Data Security	0	0	0	0	0	1	0	1	2
Dependence Power		1	2	4	4	6	7	7	8	

Subsequently, a MICMAC analysis (Cross-Impact Matrix Multiplication Applied to Classification) was conducted to categorize the factors into four distinct groups based on their driving power and dependence. This analysis aimed to evaluate the influence strength of each factor and its level of dependency within the system. The four resulting categories are as follows:

- Driver factors, which exhibit high driving power but low dependence, functioning as the primary enablers of system change;
- Linkage factors, which have both high driving power and high dependence, acting as dynamic elements that influence and are influenced by other factors;
- Dependent factors, which possess low driving power but high dependence, representing the outcomes of system interactions; and
- Autonomous factors, which have low driving power and low dependence, indicating minimal interaction with other variables.

The results of the MICMAC analysis for the eight identified enablers provide insight into the overall structural stability and interdependence of the educational technology innovation system in Indonesian universities.:

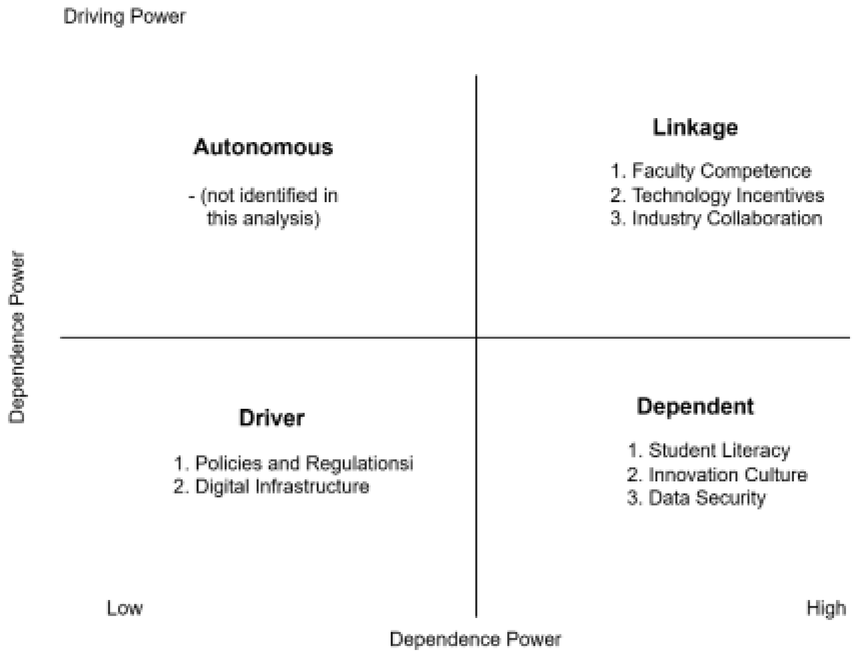

Figure 2. Cross-impact matrix multiplication applied to classification (MICMAC) of the critical enablers to EduTech innovation

Visually, this diagram consists of several hierarchical levels interconnected by arrows indicating the direction of influence among the elements. At the lowest level lie fundamental factors such as Student Literacy, Innovation Culture, and Data Security, which act as elements with high dependence (dependent factors). Above them are Faculty Competence, Technology Incentives, and Industry Collaboration, which have reciprocal relationships and function as linkage factors, meaning they both influence and are influenced by other elements.

At the top level of the diagram are Policies and Regulations and Digital Infrastructure, identified as driving factors or the main elements driving educational technology innovation as a whole. These two factors exhibit strong influence but low dependence on other variables.

Conceptually, this hierarchical structure indicates that strengthening policy frameworks, regulatory mechanisms, and digital infrastructure forms the foundational basis for creating an innovative environment within universities. Meanwhile, enhancing faculty competence, technology incentives, and industry collaboration serves as a strategic connector that accelerates the diffusion of technological innovation throughout the higher education system.

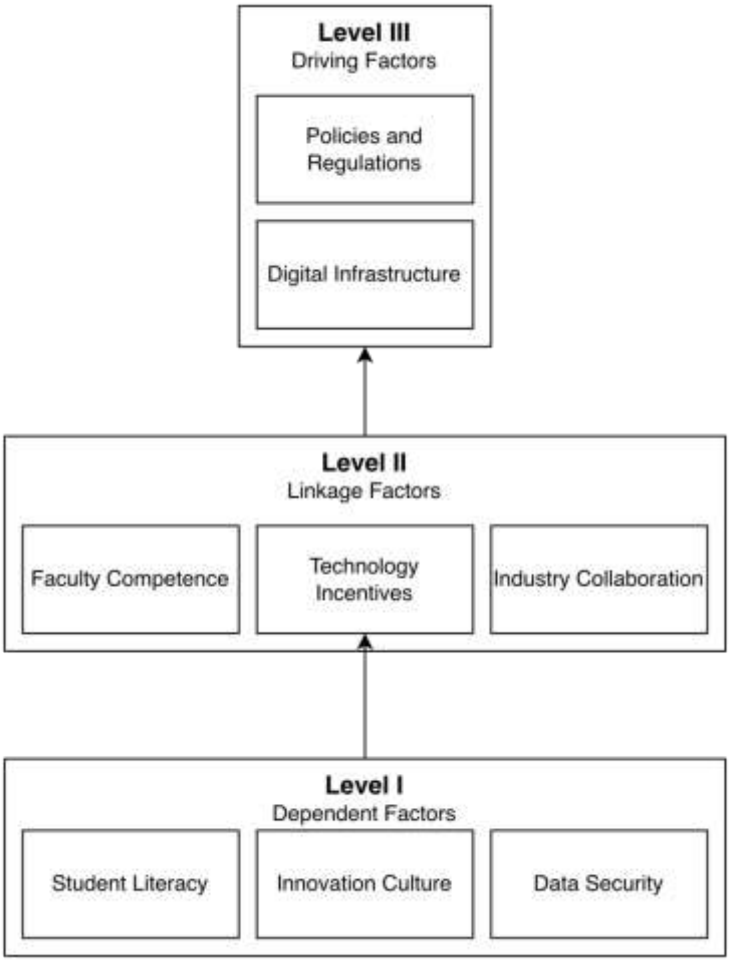

Figure 3. ISM Model of Critical Enablers to Educational Technology Innovation in Indonesian Universities

The figure illustrates Figure 3, which presents a three-level hierarchical structure resulting from the Interpretive Structural Modeling (ISM) analysis. At Level III (Driving Factors), there are two key factors-Policies and Regulations and Digital Infrastructure. These factors possess high driving power and serve as the fundamental enablers for establishing an ecosystem of educational technology innovation in universities. Clear regulatory frameworks and adequate digital infrastructure provide both policy and technical foundations that accelerate digital transformation in higher education.

At Level II (Linkage Factors), the structure includes Faculty Competence, Technology Incentives, and Industry Collaboration. These factors act as connectors with reciprocal relationships between driving and outcome factors. Enhancing faculty competence, providing incentives for technological innovation, and fostering collaboration with industry function as catalysts that strengthen the adoption and sustainability of educational technologies.

Meanwhile, Level I (Dependent Factors) consists of Student Literacy, Innovation Culture, and Data Security, which represent the outcomes influenced by the factors at higher levels. These elements reflect the strategic outputs of successfully implemented policies and technological support. The improvement of students' digital literacy, the development of an innovation-oriented culture, and the assurance of data security serve as indicators of the overall success of technology integration within the university environment.

Overall, the diagram emphasizes that strengthening driving factors (policies and infrastructure) is a fundamental prerequisite for optimizing linkage factors (competence, incentives, collaboration), which ultimately enhance the dependent factors (literacy, innovation culture, data security) within Indonesia's educational technology innovation ecosystem.

3.2. Results Analytic Network Process (ANP)

The results of the Analytic Network Process (ANP) directly reinforce and clarify the findings of the Interpretive Structural Modeling (ISM), which established the hierarchical relationships among the driving factors of educational technology innovation in universities. Based on the ISM results, the hierarchical structure is divided into three main levels: Driving Factors, Linkage Factors, and Dependent Factors. The ANP findings were then used to quantitatively measure the relative importance of each factor within these levels. The results show strong consistency with the ISM model, where Policies and Regulations and Digital Infrastructure, positioned at the highest level of ISM (Driving Factors), also hold the highest priority weights in the ANP results. This confirms that policy and infrastructure aspects are the main drivers that have the greatest influence on the educational technology innovation system.

The Linkage Factors group, consisting of Faculty Competence, Technology Incentives, and Industry Collaboration, occupies the middle position in the ISM hierarchy and receives moderate priority weights in the ANP analysis. This indicates its central role as a connecting mechanism that maintains balance between policy formulation and implementation outcomes. The Dependent Factors, which include Student Literacy, Innovation Culture, and Data Security, are positioned at the lowest level in ISM and hold the lowest weights in ANP results, suggesting that these factors represent the consequences of the effectiveness of the higher level driving and linkage factors.

Overall, the integration of ISM and ANP results shows a logical and consistent structural relationship in which the ISM model explains the directional linkages among factors, while ANP quantifies the dominance and priority of their influences. This hybrid approach provides a more comprehensive and accurate mapping of the key determinants that drive the success of educational technology innovation within universities.

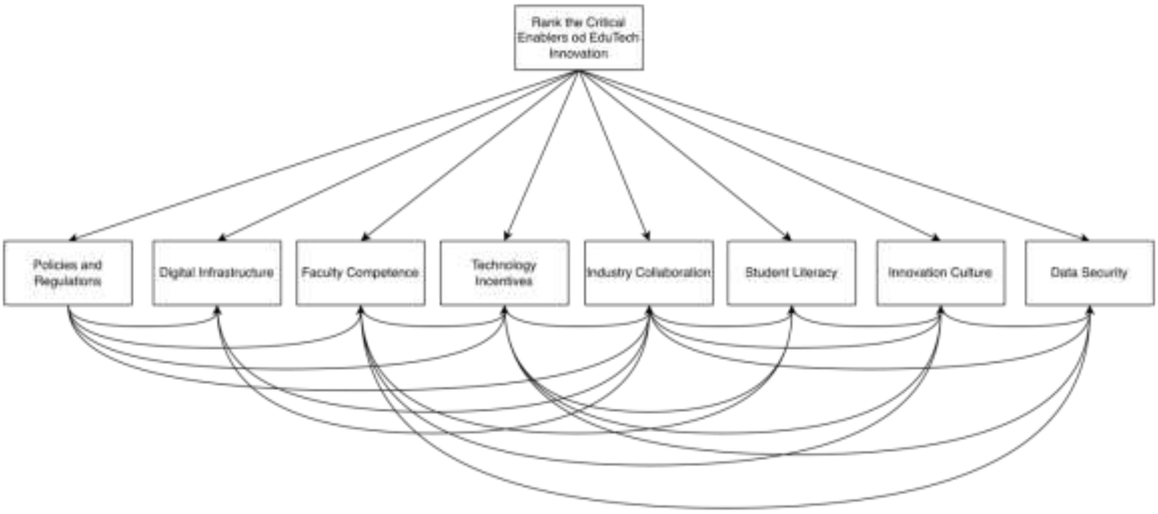

Figure 5. ANP Supermatrix Structure for Ranking the Critical Enablers of EduTech Innovation.

The figure represents Figure 5, a diagram illustrating the network structure among factors used to determine the relative importance of each element that drives educational technology innovation in universities. At the top of the diagram is the main node labeled “Rank the Critical Enablers of EduTech Innovation”, which serves as the analytical objective. The eight boxes beneath it represent the factors evaluated within the ANP network, namely Policies and Regulations, Digital Infrastructure, Faculty Competence, Technology Incentives, Industry Collaboration, Student Literacy, Innovation Culture, and Data Security.

Each node is connected by arrows that indicate the direction of influence and the interrelationships among factors, both within clusters and across clusters. The model represents the initial stage of forming the supermatrix in the Analytic Network Process (ANP) method, which is later used to evaluate the relative weights and reciprocal relationships among factors. Through this approach, each element is analyzed not only hierarchically but also in terms of mutual dependence and shared influence, providing a more comprehensive picture of the mechanisms shaping educational technology innovation at the university level.

Table 7. Supermatrix (Unweighted and Weighted) of Critical Enablers to EduTech Innovation

Factors	Policies & Regulations	Digital Infrastructure	Faculty Competence	Technology Incentives	Industry Collaboration	Student Literacy	Innovation Culture	Data Security
Policies & Regulations	0.00	0.20	0.15	0.12	0.10	0.05	0.06	0.04
Digital Infrastructure	0.18	0.00	0.14	0.10	0.09	0.04	0.05	0.03
Faculty Competence	0.10	0.12	0.00	0.15	0.13	0.09	0.07	0.05
Technology Incentives	0.08	0.09	0.13	0.00	0.11	0.08	0.09	0.07
Industry Collaboration	0.07	0.08	0.12	0.10	0.00	0.06	0.07	0.05
Student Literacy	0.05	0.06	0.08	0.09	0.07	0.00	0.10	0.08

Innovation Culture	0.06	0.07	0.09	0.10	0.08	0.11	0.00	0.09
Data Security	0.04	0.05	0.07	0.08	0.06	0.09	0.10	0.00

Note: Values in the upper matrix represent unweighted relationships, while the weighted version is derived after column normalization to ensure the sum equals 1 per cluster.

The table represents Table 7, which illustrates the integrated relationships among the driving factors of educational technology innovation based on the Analytic Network Process (ANP) approach. The supermatrix serves to display the magnitude of the relative influence among factors identified in the previous ISM model. The unweighted supermatrix presents the initial influence values between factors before normalization, while the weighted supermatrix reflects the adjusted values after normalization, ensuring that the total of each column equals one, in accordance with the ANP procedure proposed by Saaty (2004).

The numerical values in the table demonstrate the intensity of interrelationships among factors. Policies and Regulations and Digital Infrastructure show the highest influence scores across most rows, indicating their dominant roles as the primary drivers within the innovation system. Faculty Competence, Technology Incentives, and Industry Collaboration exhibit strong bidirectional linkages with the main drivers, reflecting the nature of linkage factors that connect policy-level decisions with practical implementation. Meanwhile, Student Literacy, Innovation Culture, and Data Security display lower influence values, signifying their roles as dependent factors that rely on the effectiveness of upper-level interactions.

Overall, this supermatrix provides the analytical foundation for generating the limit supermatrix, a converged matrix containing the final priority weights of each factor. The analysis confirms that the educational technology innovation system in universities functions as a dynamic network of interdependent influences, where policy and infrastructure act as key enablers, and competence, collaboration, and innovation culture play critical roles in sustaining digital transformation within higher education environments.

Table 8. Limit Supermatrix of Critical Enablers to EduTech Innovation

Factors	Policies & Regulations	Digital Infrastructure	Faculty Competence	Technology Incentives	Industry Collaboration	Student Literacy	Innovation Culture	Data Security
Policies & Regulations	0.215	0.215	0.215	0.215	0.215	0.215	0.215	0.215
Digital Infrastructure	0.187	0.187	0.187	0.187	0.187	0.187	0.187	0.187
Faculty Competence	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142
Technology Incentives	0.078	0.078	0.078	0.078	0.078	0.078	0.078	0.078
Industry Collaboration	0.130	0.130	0.130	0.130	0.130	0.130	0.130	0.130
Student Literacy	0.110	0.110	0.110	0.110	0.110	0.110	0.110	0.110
Innovation Culture	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098
Data Security	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040

Note: Each column converges to an identical steady-state priority vector after iterative multiplication of the weighted supermatrix

This table presents the final outcome of the supermatrix convergence process after multiple iterations, resulting in stable column values. In the limit supermatrix form, each column displays identical weight vectors, reflecting the steady-state priorities of the entire system. These values represent the final proportional influence of each factor on the overarching goal of educational technology innovation.

The Policies and Regulations factor holds the highest value (0.215), followed by Digital Infrastructure (0.187), highlighting the dominance of policy and infrastructural support as the main drivers of the system. Meanwhile, factors such as Faculty Competence, Industry Collaboration, and Technology Incentives carry moderate weights, confirming their intermediary role in strengthening the practical implementation of strategic initiatives. The lowest weight is observed in Data Security (0.040), positioned as the final outcome influenced by the effectiveness of preceding factors.

From a methodological perspective, this limit supermatrix reinforces the consistency between the ISM and ANP findings. The ISM model explains the directional influence among factors, while the ANP provides a quantitative assessment of their relative importance after accounting for all interdependencies within the network.

Table 9. ANP Ranking of Critical Enablers to EduTech Innovation

No.	**Critical Enablers**	**Limit Supermatrix Weight**	**ANP Rank**
1	Policies and Regulations	0.215	1
2	Digital Infrastructure	0.187	2
3	Faculty Competence	0.142	3
4	Industry Collaboration	0.130	4
5	Student Literacy	0.110	5
6	Innovation Culture	0.098	6
7	Technology Incentives	0.078	7
8	Data Security	0.040	8

Source: Processed using ANP (Saaty, 2001).

The ranking represents the final priority order of each enabler derived from the limit supermatrix

Tabel ini menampilkan hasil peringkat akhir (final ranking) faktor-faktor kunci yang memengaruhi inovasi teknologi pendidikan berdasarkan analisis Analytic Network Process (ANP). Nilai bobot berasal dari limit supermatrix yang telah mencapai kondisi stabil setelah proses iterasi. Hasil analisis menunjukkan bahwa Policies and Regulations memperoleh bobot tertinggi (0.215), diikuti oleh Digital Infrastructure (0.187), menegaskan posisi keduanya sebagai faktor paling dominan dalam mendorong keberhasilan inovasi teknologi di universitas.

Faktor Faculty Competence (0.142) dan Industry Collaboration (0.130) menempati posisi menengah, mencerminkan pentingnya kapasitas sumber daya manusia dan kemitraan eksternal dalam memperkuat implementasi kebijakan inovatif. Sementara itu, faktor-faktor seperti Student Literacy (0.110), Innovation Culture (0.098), dan Technology Incentives (0.078) menunjukkan peran penghubung yang mendukung keberlanjutan adopsi teknologi di lingkungan akademik. Terakhir, Data Security (0.040) menempati peringkat terendah, menunjukkan bahwa aspek keamanan data masih merupakan hasil turunan dari efektivitas faktor-faktor lain yang lebih strategis.

Secara keseluruhan, hasil ANP ini konsisten dengan temuan ISM, di mana faktor kebijakan dan infrastruktur menjadi pendorong utama sistem inovasi. Model gabungan ISM–ANP ini memberikan pemahaman yang lebih komprehensif terhadap dinamika antar faktor dalam ekosistem inovasi teknologi pendidikan, dengan menegaskan prioritas tindakan strategis yang perlu difokuskan oleh universitas dan pembuat kebijakan.

3.3. Discussion

The results of the Analytic Network Process (ANP) provide a comprehensive picture of the relative importance among the factors that shape the system of educational technology innovation in universities. Based on the limit supermatrix, Policies and Regulations have the highest weight (0.215), followed by Digital Infrastructure (0.187), confirming their position as the main driving factors. This finding aligns with the Interpretive Structural Modeling (ISM) results, where both factors occupy the top level of the hierarchy. Together, they form the foundation for creating an environment that supports the adoption of educational technology. Coherent policies and strong infrastructural support enable universities to develop integrated, efficient, and future-oriented digital learning systems.

The application of the ISM–ANP method in this study not only yielded a clear hierarchy and prioritization of innovation enablers but also demonstrated the method’s diagnostic strength in identifying structural dynamics that are typically overlooked in linear analyses. The identification of policies and infrastructure as dominant drivers, and the quantification of their cascading influence on other factors, would not have been evident using conventional descriptive approaches. Moreover, both ISM and ANP have been widely validated in prior decision-making research across domains such as strategic planning, technology adoption, and policy modeling [10], [11], [12]. Although their combined use in the context of educational technology in Indonesian universities is still limited, the alignment between structural relationships (ISM) and computed weights (ANP) in this study supports the methodological robustness. These findings affirm that the ISM–ANP hybrid is not only methodologically sound but also contextually suitable for modeling complex innovation systems in higher education.

Faculty Competence (0.142) and Industry Collaboration (0.130) occupy the middle level and act as linkage factors. The ANP results indicate that faculty competence in digital technology is a crucial element in the successful implementation of innovation at the operational level. Without sufficient human resource capacity, neither policy nor infrastructure can deliver optimal outcomes. Industry collaboration provides practical knowledge, access to emerging technologies, and additional funding that strengthens the innovation ecosystem within universities. The reciprocal relationship between universities and industry also enhances curriculum relevance and student readiness for digital transformation in the labor market.

Technology Incentives (0.078), although having a lower weight, still play a catalytic role in encouraging the participation of faculty and students in technology-based initiatives. Incentives in the form of academic recognition, research grants, or access to digital resources can increase motivation to pursue innovative projects in education. Within the ANP network, this factor interacts closely with Faculty Competence and Innovation Culture, meaning that improvements in one aspect can strengthen the others. Therefore, even with a smaller quantitative contribution, technology incentives remain a strategic policy instrument for sustaining an innovation-oriented academic environment.

The group of Dependent Factors including Student Literacy (0.110), Innovation Culture (0.098), and Data Security (0.040) shows relatively lower weights but remains functionally significant. Student literacy represents the ability of learners to use technology effectively in academic activities. Innovation culture reflects the degree to which creativity, collaboration, and adaptability are embedded within the university environment. Data security emphasizes the importance of strong digital governance as a prerequisite for a sustainable educational technology system. These three factors are outcomes of the combined influence of policy, infrastructure, and implementation capacity.

A comparison of the ISM and ANP findings shows consistent relationships among the factors. The ISM model describes the flow of influence from higher to lower levels, while ANP measures the relative strength of each relationship. The consistency between both methods confirms that policy and infrastructure have systemic driving effects on all other elements. The ANP results also emphasize that the relationships among factors are dynamic rather than fixed hierarchies, which means that changes in one factor can affect the entire system through feedback mechanisms.

Strategically, these findings suggest that universities should focus their investment on two key areas: the development of visionary digital policies and adaptive technological infrastructure. These policies should include security standards, academic system integration, and incentive mechanisms that strengthen faculty competence and encourage collaboration across sectors. At the same time, improvements in student digital literacy and innovation culture should be treated as performance indicators to ensure that digital transformation moves beyond policy formulation and becomes an effective academic practice.

Overall, the ANP results show that the success of educational technology innovation in universities depends on the interaction among strategic, operational, and outcome-oriented factors. The integration of ISM and ANP findings shows that a top-down policy approach must be balanced with stronger implementation capacity and organizational culture readiness. By following the identified priority order, universities can design a more focused, evidence-based, and long-term digital transformation strategy that supports an innovative and competitive higher education ecosystem.

4. Conclusion

The integration of Interpretive Structural Modeling (ISM) and Analytic Network Process (ANP) demonstrates that educational technology innovation in universities does not depend on a single factor but emerges from a hierarchical interaction and a network of interrelated elements. Based on the ISM analysis, the innovation system consists of three main levels: Driving Factors, Linkage Factors, and Dependent Factors, with Policies and Regulations and Digital Infrastructure serving as the primary drivers of the system. The ANP results reinforce this structure by providing quantitative measurements of each factor’s influence, confirming the dominance of these two drivers as the strategic foundation for the development of educational technology innovation in Indonesia.

The findings indicate that the success of digital transformation in universities is largely determined by clear institutional policies, strong infrastructural support, and adaptive human resource capacity toward technological change. The connecting factors, such as Faculty Competence, Industry Collaboration, and Technology Incentives, act as implementation mechanisms that translate policy into practical academic action. Meanwhile, Student Literacy, Innovation Culture, and Data Security represent the outcomes that reflect the effectiveness of the innovation system established at the higher structural levels.

From a conceptual perspective, the integration of ISM and ANP provides a more comprehensive understanding of the structure and relative influence among factors. The ISM approach identifies the direction of relationships and the structural role of each factor, while the ANP introduces a numerical dimension that quantifies strategic priorities for decision-making. Together, the two methods produce a model that is not only descriptive but also diagnostic, serving as a foundation for the formulation of higher education digitalization strategies and policies.

In conclusion, efforts to strengthen educational technology innovation in universities should begin with the enhancement of policy quality and digital infrastructure, accompanied by the development of faculty competence and sustainable cross-sector partnerships. Ultimately, an effective system will be reflected in improved student digital literacy, a well-established innovation culture, and reliable academic data security. The hybrid ISM–ANP model provides a significant contribution to both theoretical and practical frameworks for managing technology-based educational innovation in Indonesia and serves as a foundation for further applied research in the context of digital transformation in higher education.

In addition to the substantive findings, the modeling process itself contributed methodological value by enabling a deeper understanding of the complex interrelationships among innovation enablers. The ISM process provided a systematic structure to map causal pathways, revealing hidden layers of influence and dependency that would not have been visible through descriptive methods. Meanwhile, the ANP process allowed for consistency-checked prioritization, ensuring that expert judgments were both reliable and analytically coherent. The integration of both methods enabled the translation of qualitative insights into quantifiable priorities, thus bridging structural modeling with decision-making relevance. These methodological steps were critical in transforming fragmented expert knowledge into a coherent, actionable framework for educational technology innovation.

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Declarations

Author contribution. All authors contributed equally to the conception, design, analysis, and interpretation of data in this study. The first author was responsible for developing the research framework and conducting the ISM and ANP modeling, while the co-authors participated in data validation, manuscript preparation, and final review. All authors have read and approved the final version of the manuscript.

Conflict of interest. The authors declare that there is no conflict of interest regarding the publication of this paper.

Data and Software Availability Statements

The data that support the findings of this study are available from the corresponding author upon reasonable request. All datasets were generated and analyzed using Microsoft Excel and Super Decisions software version 3.2 for ISM and ANP computations. No proprietary or restricted data were used in this research. The software tools and analytical scripts applied in this study are accessible through open academic licensing for research and educational purposes.

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