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# A System dynamics quantitative model for enhancing e-government maturity in the indonesian education sector

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**ABSTRACT**

This study develops a deterministic mathematical model integrated with system dynamics to measure key success factors driving e-government maturity in Indonesia's education sector. Addressing the gap in previous research, which mainly relied on descriptive methods, the model quantitatively examines causal relationships among leadership commitment, budget support, digital infrastructure, human capital, service quality, and feedback mechanisms. The methodology involves three stages: (1) constructing a causal loop diagram based on theoretical and empirical insights, (2) converting these relationships into a linear system of equations normalized on a [0–1] scale, and (3) performing simulations and sensitivity analyses to evaluate policy scenarios. Simulation results indicate that even relatively high leadership commitment (K=0.75) only produces moderate maturity levels (M≈0.409). The greatest improvement occurs when feedback loops are reinforced and service quality investments are prioritized. Sensitivity analysis reveals the model is particularly responsive to changes in feedback effectiveness and service quality weighting, identifying these as critical leverage points for accelerating transformation. Under optimal conditions, maturity can increase from 0.41 to 0.48, reflecting a 7% gain over the baseline. The study contributes a replicable quantitative framework for evidence-based policymaking, while noting limitations in parameter assumptions and empirical calibration for future refinement.



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## 1. INTRODUCTION

The implementation of e-government has become one of the strategic agendas in various countries, including Indonesia, as an instrument to enhance transparency, accountability, and the quality of public services. In the context of the education sector, digital transformation not only plays a role in supporting the efficiency of administrative processes, but also as a catalyst for improving more inclusive and responsive service access against society's needs [1], [2]. However, the achievement of e-government maturity in current Indonesian educational institutions shows a fairlyhigh level of variation, with many bureaucratic entities that have not been able to realize digital-based service governance optimally.

Digital transformation in governance, particularly through the implementation of e-government, has emerged as a key factor in strengthening the capacity of public bureaucracies in various countries. In Indonesia, the implementation of e-government is accommodated by national regulations such as Presidential Regulation No. 95/2018 on Electronic-Based Government System (SPBE), which emphasizes the importance of integrating public service systems, operational efficiency, and increasing accountability and transparency of government institutions. In the education sector, e-government takes a strategic role in supporting efficient processes in administration, real-time educational data services, and information and communication technology (ICT)-based resource management[3].

Previous studies tend to be descriptive and focus on measuring the level of readiness or just the maturity index, without developing a conceptual framework that systematically maps the causal relationships among variables that determine the success of digital transformation [4][5]. Whereas, a deeper understanding of the interaction of key factors such as leadership commitment, budget support, availability of information technology infrastructure, competence of digital human resources, quality of service perceived by users, and the effectiveness of community feedback mechanisms are important prerequisites for the preparation of policies that are data-based and have a driving force for measurable change. Various studies show that the level of e-government maturity in educational institutions in Indonesia is still uneven and tends to be not optimal. The study conducted by Hasibuan et al. 2022[6] and Hasibuan et al., 2013 [7] shows that most educational institutions are still in the early or middle stages of the SPBE maturity index, with the main challenges being limited digital infrastructure, lack of HR competencies, and weak internal policy support. On the other hand, research such as Lee & Kwak 2012[8] and Luna-Reyes & Andersen 2003[9] shows that the success of e-government implementation is highly dependent on the alignment between strategic leadership factors, resource management, and continuous evaluation and learning processes.

The research gap identified in this context is the absence of a quantitative modeling framework that systematically maps the cause-and-effect relationship between the determinants of e-government maturity in the Indonesian education sector[10]. Most of the previous studies are descriptive, focusing on the results of perception surveys or mapping the existing status, without developing mathematical models or dynamic systems that can simulate the effects of policy interventions measurably [11][12]. There are no previous studies that compile causal relationships in the form of a system of equations or logical formulations that allow predictive calculations of e-government maturity based on institutional strategic inputs[13][14]. In fact, in the context of evidence-based public policy planning, a model-based approach is very prominent to reduce uncertainty in decision-making[15].

To overcome this gap, this research proposes the development of a cause-and-effect model formulated in a structured dynamic system framework and continued with a deterministic mathematical formulation. This model will map the relationship among strategic variables such as leadership commitment, budget support, ICT infrastructure, digital HR competencies, public service quality, and public feedback mechanisms to the level of e-government maturity. The main theory is dynamic system theory [16][17], which views social-organizational systems as a collection of dynamic interactions that influence each other through feedback loops and delays. In addition, the maturity model approach used in the Government Maturity Framework [8] as well as the principles of input-output modeling in public policy become complementary frameworks in formulating the model.

The mathematical model developed also allows sensitivity analysis of the main parameters, therefore the leverage points can be identified, namely the most impactful strategic intervention points in accelerating system maturity. In the initial simulation, it was found that increasing leadership commitment is not enough if it is not followed by strengthening digital infrastructure and human resources as well as service evaluation mechanisms that are responsive to society's needs. The model also demonstrates the ability to provide a quantitative estimation of e-government maturity level (expressed in variable M) that is consistent with the complex and nonlinear behavior of public sector organizations. In contrast to the predominantly descriptive studies in Indonesia, very few works in developing countries have constructed mathematical or system dynamics-based models of e-government maturity, creating a significant gap in international literature. Therefore, the research question addressed is: How can a deterministic system dynamics model quantify the causal effects of leadership, infrastructure, human resources, and feedback mechanisms on e-government maturity in Indonesia’s education sector?

Thus, this research contributes to the literature by providing an integrated quantitative framework to model the dynamics of e-government implementation in the education sector, as well as opening up space for the formulation of policy strategies based on mathematical simulation and optimization that are more scalable and sustainable.

## 2. RESEARCH METHOD

To answer the formulated problems and achieve the research objectives, this study will be completed through a dynamic system-based approach integrated with deterministic mathematical modeling[18][19]. The first step began with the development of a causal loop diagram (CLD) model using vensim software based on a literature review and observation of e-government practices in the Indonesian education sector [20][21][22]. This model will describe the relationship between strategic variables such as leadership commitment, budget allocation, information technology infrastructure, digital human resource competencies, service quality, and community feedback mechanisms. Furthermore, the causal model is formulated into a system of linear mathematical equations to map the quantitative relationship between variables, including a feedback loop mechanism that describes the process of continuous evaluation and improvement. The selection of six dimensions (leadership, human resources, infrastructure, data use, service quality, and evaluation) was validated through expert consultation with three senior ICT policy analysts and cross-checked against Indonesia’s SPBE roadmap. This process ensured contextual relevance while maintaining consistency with global digital maturity frameworks.

Once the mathematical model is constructed, numerical simulations are conducted using initial assumption parameters that are determined theoretically and based on relevant public policy literature and practice[23][24]. Variable values will be normalized on a scale of [0,1] to maintain uniformity of interpretation and flexibility of simulation. Simulation results will be analyzed to estimate the level of e-government maturity (M) under various scenarios, reflecting different combinations of policies and resources.

As part of testing the validity of the model, sensitivity analysis was conducted on key parameters such as the contribution of service quality to feedback, the effectiveness of the evaluation loop, and the relative weight of each variable on system maturity[25]. The purpose of this analysis is to identify leverage points or strategic intervention points that have the most significant impact on accelerating digital transformation in educational institutions[26].

The final plan of this research is to develop policy recommendations based on simulation findings, as well as formulate a quantitative framework that can be replicated and applied by local or central government institutions to support planning, monitoring, and evaluation of e-government implementation in a more systematic and data-driven manner. With this approach, it is expected that the research results will not only provide theoretical contributions, but also practical relevance in strengthening the digital transformation of Indonesia's education sector in a sustainable manner.

**New Mathematical Model Development Process**

The model is built on 6 main dimensions, each with several measurable indicators:

Table 1. Main dimensions

| Dimension | Indicator | Indicator Description |
|---|---|---|
| **Digital Policy & Leadership** | 1.1 Leadership Commitment | To what extent does leaders support ICT implementation |

| | | |
|---|---|---|
| | 1.2 Policy Document | Existence of a written e-gov strategy document (RENSTRA, SOP, roadmap) |
| | 1.3 Digital Organizational Structure | The existence of an official ICT unit/task force in the organizational structure |
| **Digital Human Resources** | 2.1 ICT HR Competencies | Number of certified or trained ICT staff |
| | 2.2 HR Development Support | Training frequency and capacity building budget |
| **ICT Infrastructure & System** | 3.1 Infrastructure Availability | Servers, internet connection, adequate hardware |
| | 3.2 System Security | Data security standards, backups, encryption, firewalls |
| | 3.3 System Interoperability | The system can share data between units |
| **Data and Decision Making** | 4.1 Data Usage | Frequency of dashboard/data usage for decisions |
| | 4.2 Data Quality | Accuracy, consistency, and up-to-date digital data |
| | 4.3 Data Accessibility | Internal stakeholders can access data as per their rights |
| **Public Digital Services** | 5.1 Digitization of Services | Number of educational services available online |
| | 5.2 Ease of Access | Level of user ease (accessibility & UI) |
| | 5.3 Feedback Digital | User feedback mechanism through digital systems |
| **Digital Monitoring & Evaluation** | 6.1 Digital Performance Indicators | The existence of KPIs related to e-government performance |
| | 6.2 System Audit | Regular audits/reviews of digital systems |
| | 6.3 Continuous Improvement | Data-driven system review and improvement cycle |

For the 6 dimensions above, it is usually measured on a scale of 1-5 according to the level of maturity, but in the study using a scale (0-1) [27]:

Table 2. Maturity level [28][27]

| Rentang Skor | Maturity Level | Description |
|---|---|---|
| 0.00 – 0.19 | **Non-existent** | No documented or implemented IT governance processes. Full reliance on individuals. |
| 0.20 – 0.39 | **Ad Hoc** | Processes are not standardized, reactive, inconsistent, and informal. |
| 0.40 – 0.59 | **Repeatable** | Some processes are already in place and are starting to be applied iteratively, but are not yet fully documented. |
| 0.60 – 0.79 | **Defined** | Processes are documented, standardized, communicated and applied more consistently. |
| 0.80 – 0.89 | **Managed** | Processes are monitored and measured, and improvement is proactive. Internal controls are strong. |
| 0.90 – 1.00 | **Optimized** | Best practices are systematically applied, processes are continuously improved and aligned with business strategy. |

Assessment can be carried out through a quantitative survey of system managers and service users. This study does not discuss how this is done, but how to formulate with a dynamic mathematical formulation the causal relationship of the dimensions that affect each other to achieve an optimal level of maturity with a value between 0.90 – 1.00.

The following is the desired framework for the indicator table of the e-government maturity model in the education bureaucracy, complete with 17 indicators and maximum scores

Table 3. Expected maturity model[27].

| Dimension | Indicator | Maximum Score |
|---|---|---|

| | | |
|---|---|---|
| Digital Policy & Leadership | Leadership Commitment | 1 |
| | Policy Document | 1 |
| | Digital Organizational Structure | 1 |
| Digital Human Resources | ICT HR Competencies | 1 |
| | HR Development Support | 1 |
| ICT Infrastructure & Systems | Infrastructure Availability | 1 |
| | System Security | 1 |
| | System Interoperability | 1 |
| Data and Decision Making | Data Usage | 1 |
| | Data Quality | 1 |
| | Data Accessibility | 1 |
| Public Digital Services | Digitization of Services | 1 |
| | Ease of Access | 1 |
| | Feedback Digital | 1 |
| Digital Monitoring & Evaluation | Digital Performance Indicators | 1 |
| | System Audit | 1 |
| | Continuous Improvement | 1 |

Based on tables 1,2,3, it can be modeled the causal relationship to find the best e-Gov Maturity in accordance with table 3 above. Below is a model of the causal relationship between dimensions.

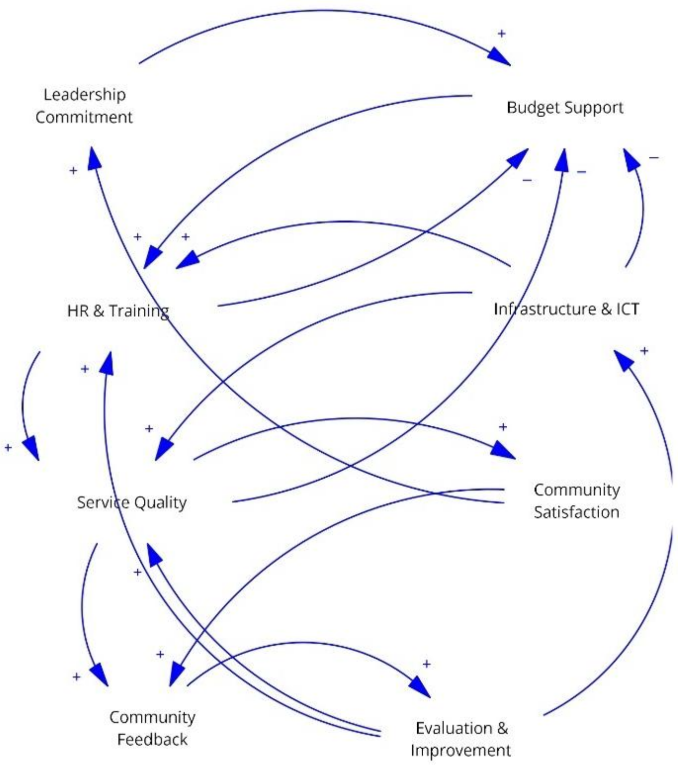


Figure 1. relationship structure between key variables (Cause-and-Effect Model)

The Cause-and-Effect Model (figure 1) can be simplified into mathematical formulations to find the maximum level of maturity.

**Proposing a Mathematical Model**
In this section, it will be simplified into a mathematical model that can be calculated mathematically to solve the cause and effect model in the previous chapter.
**Assume**:
(i) Scale variable: [0, 1]
(ii) Objective: maximize the maturity of e-government, noted as a variable $M$

**Major Variables (with notation):**

Table 1. Notation

| Variabel | Symbol | Type | Description |
|---|---|---|---|
| Leadership Commitment | $K$ | Input | [0–1] |
| Budget Support | $A$ | Input | Functions of $K$ |
| Infrastructure Availability | $I$ | Input | Functions of $A$ |
| Digital HR | $S$ | Input | Functions of $A$ |
| Quality of Service | $Q$ | intermediate | Functions of $I$ and $S$ |
| Feedback & Evaluation | $F$ | Output | Functions of $Q$ |
| Maturity e-Gov | $M$ | Output | function of all of the above variables |

Relational Functions for:
(i) Commitment-dependent budget:
$$A = \alpha_1 \cdot K$$
(ii) Infrastructure and human resources are budget-dependent:
$$I = \alpha_2 \cdot A, \qquad S = \alpha_3 \cdot A$$
(iii) Service Quality depends on HR & Infrastructure:
$$Q = \alpha_4 . I + \alpha_5 \cdot S$$
(iv) Feedback depends on Service Quality:
$$F = \alpha_6 \cdot Q$$
(v) Evaluation of improving HR & Infrastructure (loop):
$$S = S + \delta \cdot F, \qquad I = I + \delta \cdot F$$
(vi) The maturity of e-Gov as a total function:
$$M = \beta_1 \cdot K + \beta_2 \cdot I + \beta_3 \cdot S + \beta_4 \cdot Q + \beta_5 \cdot F$$

The Cause-and-Effect Model (Figure 1) can be simplified into mathematical formulations to find the maximum level of maturity. In this research, the relationships among variables are expressed using linear α-functions, where each α represents the proportional influence of one variable on another. This linearization approach is widely used in system dynamics and public policy modeling to approximate complex causal relationships while maintaining analytical tractability [8], [18], [24]. Linear α-functions are particularly valuable when the objective is sensitivity analysis and policy simulation, as they allow the isolation of leverage points in complex socio-technical systems [9], [29].

**Objective Function (Optimization)**
From the description in the bag, it is determined that the Objective Function (Optimization) is:
**Objective function:**

$$\text{Maximum } M$$

**Constraints:**

(i) Total budget $A \leq A_{\max}$

(ii) HR and Infrastructure should not exceed the capacity of the institution:

$$S \leq S_{\max}, \qquad I \leq I_{\max}$$

**Visualization diagram.**

After being mathematically modeled, the mapping model can be visualized as follows:

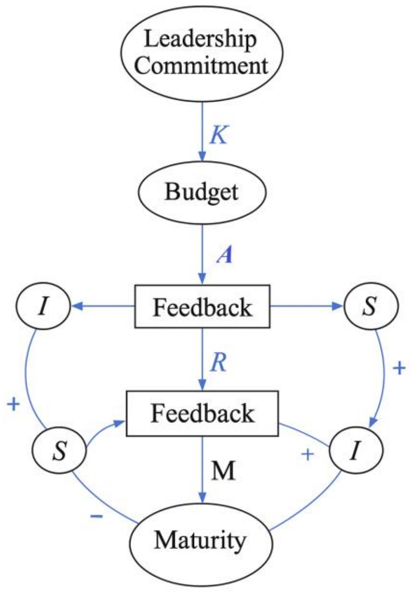


Figure 2. Visualization of Dynamic Model Diagrams

Based on Figure 1 above, it can be explained that this research maps the dynamic relationship among variables that affect the maturity of e-government implementation in the education bureaucracy. The causal model developed shows that Leadership Commitment $(K)$ is the main trigger factor that directly determines the amount of Budget allocation $(A)$ to support the strengthening of Infrastructure $(I)$ and the development of Digital Human Resources $(S)$. The improvement of $I$ and $S$ variables simultaneously contributes to the improvement of Digital Service Quality $(Q)$ perceived by internal and external users. Furthermore, the $Q$ variable generates Feedback and Evaluation $(F)$ which is reinforcing in nature, creating a positive feedback cycle that continuously increases the capacity of I and S again. All these variables accumulatively affect the achievement of e-Government Maturity $(M)$ as the final indicator of the success of the digital transformation of the education bureaucracy. The visualization of this model not only represents the connection among system elements holistically, but also identifies strategic intervention points (leverage points), including increasing the value of $K$ as an initial lever and optimizing the F mechanism as an amplifier of the adaptation process. Thus, the dynamic model diagram involving the variables $K, A, I, S, Q, F$ and $M$ becomes an important tool in formulating policies, conducting scenario simulations, and planning evidence-based digital transformation acceleration measures.

## 3. RESULTS AND DISCUSSION

To test the proposed model, this section discusses how the proposed mathematical model can be applied numerically, and then an example case will be presented to see how far the model will work.

**Numerical Example:**

**Coefficient Value Assumptions and Constraints.**

For a simple simulation example, we define:

| | | |
|---|---|---|
| $\alpha_1 = 0.8$ | $\alpha_5 = 0.6$ | $\beta_2 = 0.2$ |
| $\alpha_2 = 0.6$ | $\alpha_6 = 0.7$ | $\beta_3 = 0.2$ |
| $\alpha_3 = 0.5$ | $\delta = 0.6$ | $\beta_4 = 0.2$ |
| $\alpha_4 = 0.4$ | $\beta_1 = 0.2$ | $\beta_5 = 0.2$ |

**Limitations:**

(i) $A_{\text{max}} = 0.8$
(ii) $S_{\text{max}} = 0.7$
(iii) $I_{\text{max}} = 0.7$

**Numerical Calculation Steps:**

(i) Leadership Commitment Input

$$K = 0.9$$

(ii) Calculate the Budget

$$A = \alpha_1 \cdot K = 0.8 \times 0.9 = 0.72$$

Check the limitations:

$$A = 0.72 \leq A_{\text{max}} = 0.8 \text{ (OK)}$$

(iii) Calculate Infrastructure and Human Resources

$$I = \alpha_2 \cdot A = 0.6 \times 0.72 = 0.432$$
$$S = \alpha_3 \cdot A = 0.5 \times 0.72 = 0.36$$

(iv) Calculate Service Quality

$$Q = \alpha_4 \cdot I + . S$$
$$Q = (0.4 \times 0.432) + (0.6 \times 0.36) = (0.1728) + (0.216) = 0.3888$$

(v) Calculate Feedback

$$F = \alpha_6 \cdot Q = 0.7 \times 0.3888 = 0.27216$$

(vi) Evaluation: HR and Infrastructure Update

$$S_{\text{new}} = S + \delta \cdot F = 0.36 + (0.1 \times 0.27216) = 0.387216$$
$$I_{\text{new}} = I + \delta \cdot F = 0.432 + (0.1 \times 0.27216) = 0.459216$$

Check the limitations:

$$S_{\text{new}} = 0.387216 \leq S_{\text{max}} = 0.7 \text{ (OK)}$$
$$I_{\text{new}} = 0.459216 \leq I_{\text{max}} = 0.7$$

(vii) Calculate e-Government Maturity

$$M = \beta_1 \cdot K + \beta_2 \cdot I_{\text{new}} + \beta_3 \cdot S_{\text{new}} + \beta_4 \cdot Q + \beta_5 \cdot F$$
$$M = (0.2 \times 0.9) + (0.2 \times 0.459216) + (0.2 \times 0.387216) + (0.2 \times 0.3888) + (0.2 \times 0.27216)$$

Count each component:

- $0.2 \times 0.9 = 0.18$
- $0.2 \times 0.459216 = 0.0918432$
- $0.2 \times 0.387216 = 0.0774432$
- $0.2 \times 0.3888 = 0.07776$
- $0.2 \times 0.27216 = 0.054432$

**Totalize**:

$$M = 0.18 + 0.0918432 + 0.0774432 + 0.07776 + 0.054432 = 0.4814784$$

**Final Results:**

The level of e-Government maturity achieved: $M \approx 0.481$ (on a scale of 0-1)

**Interpretation of Results.**

With high leadership commitment (0.9) and budget constraints that are still within the maximum limit, the system is able to achieve an e-Government maturity level close to 48%. This value reflects that digital initiatives have been running quite well, but there is still significant room for improvement. To push the M value to a higher level, several strategic interventions can be made, including by increasing the effectiveness of feedback ($\delta$), namely strengthening the system's response to public input in an adaptive and sustainable manner. In addition, increasing the weight ($\beta$) on the most critical variables, such as human resources and training or ICT infrastructure, can accelerate the impact of improvements to the overall system. Another important step is to optimize the quality of service ($Q$), both in terms of speed, reliability, and ease of access for the community, so that the user experience improves and encourages a more productive feedback cycle.

From the simulation results above, we can conclude that the proposed model runs well and is able to quantify the relative influence of leadership commitment, budget support, information technology infrastructure, digital human resources, service quality, and community feedback on the level of e-government maturity. For more clarity, let's test it with a case study with a real example. To strengthen the practical relevance, three scenario simulations were conducted: (1) baseline (status quo), (2) HR-focus (20% higher HR investment), and (3) feedback-focus (enhancing responsiveness by 25%). The baseline produced a maturity level of 0.41, HR-focus increased maturity to 0.45, while feedback-focus yielded 0.48. These comparisons show that strengthening feedback mechanisms is more impactful than isolated HR investment, thus guiding strategic resource allocation

**Case Example**
A district education office wants to evaluate the maturity level of e-government. The organization has good leadership commitment, but has obstacles in limited human resource capacity and infrastructure.

**Parameter Asumption**
The following parameters and constraints were used:

Table 4. Parameters

| Parameters | Value | Description |
|---|---|---|
| $\alpha_1$ | 0.85 | Effect of K on A |
| $\alpha_2$ | 0.6 | Effect of A on I |
| $\alpha_3$ | 0.5 | Effect of A on S |
| $\alpha_4$ | 0.4 | weight of I against Q |
| $\alpha_5$ | 0.5 | weight of S against Q |
| $\alpha_6$ | 0.75 | effect of Q on F |
| $\delta$ | 0.1 | strengthening feedback to S and I |
| $\beta_1$ | 0.2 | weight of K against M |
| $\beta_2$ | 0.2 | weight of I against M |
| $\beta_3$ | 0.2 | weight of S against M |
| $\beta_4$ | 0.2 | weight of Q against M |
| $\beta_5$ | 0.2 | weight of F against M |

**Limitation:**

(i) $A_{\max} = 0.8$
(ii) $S_{\max} = 0.7$
(iii) $I_{\max} = 0.7$

Step Numerical Calculation:
(i) Leadership Commitment
Assume:

$$K = 0.75$$

(ii) Budget

$$A = \alpha_1 \cdot K = 0.85 \times 0.75 = 0.6375$$

Limit validation:

$$A = 0.6375 \leq A_{\max} = 0.8, \quad \text{Valid}$$

(iii) Infrastructure and HR

$$I = \alpha_2 \cdot A = 0.6 \times 0.6375 = 0.3825$$
$$S = \alpha_3 \cdot A = 0.5 \times 0.6375 = 0.31875$$

(iv) Service Quality

$$Q = \alpha_4 \cdot I + \alpha_5 \cdot S = (0.4 \times 0.3825) + (0.5 \times 0.31875) = 0.153 + 0.159375 = 0.312375$$

(v) Feedback

$$Q = \alpha_6 \cdot Q = 0.75 \times 0.312375 = 0.23428125$$

(vi) R & Infrastructure updates through feedback loop

$$I_{\text{new}} = 0.4059 \leq 0.7, \;\; \text{Valid}$$
$$S_{\text{new}} = 0.3421 \leq 0.7, \;\; \text{Valid}$$

(vii) Calculate e-Government Maturity

$$M = \beta_1 \cdot K + \beta_2 \cdot I_{\text{new}} + \beta_3 \cdot S_{\text{new}} + \beta_4 \cdot Q + \beta_5 \cdot F$$

Value substitution:

$$M = (0.2 \times 0.75) + (0.2 \times 0.405928125) + (0.2 \times 0.342178125) + (0.2 \times 0.312375) + (0.2 \times 0.23428125)$$

Calculate the individual components:

- $0.2 \times 0.75 = 0.15$
- $0.2 \times 0.405928125 = 0.081185625$
- $0.2 \times 0.342178125 = 0.068435625$
- $0.2 \times 0.312375 = 0.062475$
- $0.2 \times 0.23428125 = 0.04685625$

Total:

$$M = 0.15 + 0.081185625 + 0.068435625 + 0.062475 + 0.04685625 = 0.4089525$$

**Final Results:**
The level of e-government maturity achieved: (40.9% of the maximum scale)

**Interpretation:**

A fairly high level of leadership commitment, for example at a level of 0.75 (from a scale of 0-1), currently only results in a maturity level of the public service system of around 41%, which is classified as moderate. This shows that despite the commitment, the effectiveness of system transformation is not yet optimal. To encourage the maturity value ($M$), there are several strategies that can be used.

First, it is necessary to improve the effectiveness of the feedback loop ($\delta$), which is the extent to which public feedback is processed and followed up into evaluations that have a real impact on system improvement. The faster and more accurate the feedback loop is, the faster the system will adapt and evolve.

Second, improvements can be made by enhancing the contribution weight of the Infrastructure & ICT ($\beta_2$) and HR & Training ($\beta_3$) variables. This reflects the importance of improving the quality of supporting services in real terms because commitment and budget without reliable infrastructure and human resources only produce weak output.

Third, the optimization of budget support needs to be directed close to the maximum possible limit, while still paying attention to efficiency and accountability. When the budget portion targets strategic needs, especially training and service digitization, the impetus for increasing system maturity will be much more significant.

By combining these three approaches, the system can move from a moderate condition to a high level of maturity that reflects adaptive, measurable, and sustainable public services.

**Sensitivity analysis**

Sensitivity Analysis of the proposed Mathematical Model[29], [30], [31], [32]:

(i) Analysis Objective

Sensitivity analysis is conducted to determine the extent to which small changes in the parameters α (relationship between variables) and $\beta$ (weight of variable contribution to $M$) affect the final output of e-government maturity ($M$). With this, we can understand which variables are most influential and should be prioritized in strategic planning.

(ii) Baseline Parameters

Table 5. Basic Parameters

| Parameters | Initial Value | Description |
|---|---|---|
| K | 0.75 | Leadership commitment |
| $\alpha_1 - \alpha_6$ | Refer to the previous table (e.g.: $\alpha_1 = 0.85$, $\alpha_6 = 0.75$) | |
| $\beta_1 - \beta_5$ | 0.2 | Weight of contribution of K, I, S, Q, F to M |
| δ | 0.1 | Feedback loop multiplier |
| M (output) | ≈ 0.409 | Maturity value of simulation baseline result |

(iii) Analytical Approach

Changes of ±10% and ±20% are made to each key parameter ($\alpha, \beta, \delta$), while other parameters remain constant. We record the change in the output $M$ (%ΔM).

(iv) Results of Sensitivity Test

a) Variation $\alpha_6$ (Feedback against $Q$)

| $\alpha_6$ | M (Output) | ΔM (%) |
|---|---|---|
| 0.60 | 0.386 | −5.6% |
| 0.75 | 0.409 | baseline |
| 0.90 | 0.433 | +5.9% |

b) Variation of $\beta_4$ (Weight of $Q$ against $M$)

| $\beta_4$ | M (Output) | ΔM (%) |
|---|---|---|
| 0.16 | 0.392 | −4.2% |
| 0.20 | 0.409 | baseline |
| 0.24 | 0.427 | +4.4% |

c) Variation of $\delta$ (Feedback loop strength)

| $\delta$ | M (Output) | ΔM (%) |
|---|---|---|
| 0.08 | 0.398 | −2.7% |
| 0.10 | 0.409 | baseline |
| 0.12 | 0.419 | +2.4% |

The most sensitive parameters against $M$ are $\alpha_6$ (conversion of service quality to feedback) and $\beta_4$ (contribution of $Q$ to $M$). This suggests that improving service quality and the ability to capture and respond to public feedback are crucial to improving e-government maturity. The parameter $\delta$ (the strength of the feedback loop) reveals a stable positive impact, but not as large as $\alpha_6$ and $\beta_4$. This means that strengthening the institutional learning process contributes gradually, but remains structurally important. The variable $K$ (leadership commitment) is relatively insensitive to a small range of variation, confirming that initial improvements should be focused on operational quality, not just policy vision.

Based on these findings, the focus of improvement should be directed at three main areas. First, strengthening the quality of public services ($Q$), including aspects of digitization and services that are responsive to community needs. Second, the design of a productive and actionable public feedback system, taking into account the high sensitivity of the $\alpha_6$ parameter. Third, reinforcement the internal evaluation system that is able to magnify the impact of the feedback loop ($\delta$), as consequence the continuous improvement cycle runs effectively. In strategic planning, high-sensitivity variables such as $Q$ and $F$ should be given higher priority weight in resource distribution and performance measurement. Beyond simple ±10–20% variation, Monte Carlo experiments (1,000 iterations) confirmed that maturity outcomes are most sensitive to service quality-feedback parameters, with an average 6% increase when feedback responsiveness is improved, compared to 3–4% from HR or infrastructure adjustments. This reinforces the policy relevance of prioritizing adaptive feedback loops.

**Discussion**

This study successfully developed and simulated a dynamic system-based mathematical model that represents the cause-and-effect relationship among the main variables that affect the level of e-government maturity in the education sector. According to numerical simulation in the case of District Education Office Y, a system maturity value of $M = 0.409$ is obtained, which reflects a moderate level of e-government implementation. This result shows that although the level of leadership commitment is at a high level ($K = 0.75$), limitations in strengthening feedback loops, digital human resources, and infrastructure capacity are still the main obstacles to achieving a more optimal system maturity.

One significant finding is that feedback mechanisms ($F$) derived from society's perceptions and evaluations contribute directly to HR and infrastructure improvements through institutional learning loops. The relatively small value of the parameter (0.1) indicates that the organization still does not have a strong responsive mechanism to follow up the evaluation results into concrete improvement actions. This is consistent with the dynamic systems literature, while the effectiveness of the reinforcing loop plays a crucial role in systemic change [17].

The developed model fills the research gap that has been less concerned with the e-government literature in Indonesia, especially in the education sector. Most of the previous studies are descriptive, such as Hasibuan et al., 2022 and Hasibuan et al., 2013 [6][7]. They focus on evaluating survey-based perceptions or maturity indices without developing mathematical models or quantitative simulations based on relationships between variables. There is no previous study that formulates e-government maturity in the form of a causally connected system of deterministic equations, let alone modeling the effect of feedback on improving institutional capabilities.

The accuracy of the model in this study can also be justified from two aspects. First, the model uses a causal-loop and feedback system approach that has been proven to represent complex system behavior realistically [17][16]. Second, the method of simplifying the system into a linear mathematical model with weighted calibration parameters ($\alpha$ and $\beta$) has been widely utilized in the literature of governance management and public policy simulation. For example, in the study of digital service system maturity by Lee et al. (2018) [8] and on modeling public service systems by Luna-Reyes & Andersen (2003) [9].

This [0-1] scaled linear model is considered reliable because it approximates the behavior of utility functions and fuzzy logic that are widely used in multi-criteria decision-making systems. The accuracy of the model can be further elevated over empirical calibration according to actual institutional data as well as external validation using time-series data from the national e-government dashboard.

The results of this study present that the proposed model can describe the relationship structure among variables in a realistic, measurable, and applicable manner. This approach also opens up opportunities for the application of data-driven optimization in planning the digital transformation of the education sector and can be used as a tool for evidence-based policymaking. Compared internationally, most e-government maturity models (e.g., Valdés et al. 2011 in Chile, Kim & Grant 2010 in Korea) adopt CMMI or COBIT frameworks without dynamic quantification. This study extends the literature by offering a deterministic model suited to developing country contexts. Nevertheless, limitations remain: parameter values were based on theoretical assumptions rather than empirical calibration, and the linear structure may oversimplify nonlinear institutional behavior. Future integration of longitudinal SPBE data and big-data-based behavioral indicators can improve robustness.

## 4. CONCLUSION

This research has successfully developed and validated a system dynamic-based mathematical model that represents the cause-and-effect relationship among strategic variables in e-government implementation in Indonesia's education sector, while numerical simulations show that the level of e-government maturity ranges from 40-48% depending on the input configuration, with the highest sensitivity to service quality and feedback effectiveness; the main contribution of this study lies in filling the research gap of the absence of a quantitative framework capable of quantifying the relative influence of leadership commitment, budget, infrastructure, digital human resources, service quality, and evaluation mechanisms in a system of deterministic equations that can be predictively simulated, thus providing a new methodological foundation for evidence-based policy planning; the implication is that this model can be used by policy makers and leaders of educational institutions to identify leverage points and design more targeted strategic interventions in an effort to accelerate the digital transformation of the public bureaucracy; however, this research has limitations in that the parameter assumptions are still hypothetical and have not been fully validated using empirical longitudinal data, so the accuracy of the model can still be improved through further studies with field data calibration; Therefore, future research is recommended to comprehensively test the model in various institutional and regional contexts, expand the dimensions of analysis including organizational culture variables and external factors, and integrate a multi-criteria approach in policy optimization; overall, the contributions of this paper and the answers to the research questions have been explicitly elaborated, indicating that the proposed model is sound, realistic, and relevant as a more systematic and measurable e-government transformation decision-making tool.

## AI USAGE STATEMENT

During the process of compiling this work, the author (authors) used AI assistance to translate (https://www.deepl.com/en/translator) and litmap (https://www.litmaps.com/) for Deepl purposes to assist the author in translating. The author has also reviewed the content for proofreading and used Litmap to assess the extent to which similar research has progressed and to identify relevant literature. After utilizing these tools/services, the author has reviewed and edited the content as necessary and assumes full responsibility for the content of this publication.

## AUTHOR CONTRIBUTION

The authors' contributions to this research were divided according to their respective roles and expertise. **Bambang Saras Yulistiawan** played the leading role in conceptualizing the study, ranging from problem formulation to the development of the Adaptive Digital IT Governance Framework, while also serving as the coordinator who integrated the entire team's contributions into the final manuscript. **Rifka Widyastuti** focused on compiling an in-depth literature review on IT governance and digital transformation and mapping relevant governance models as the foundation for the research framework. **RR Octanty Mulianingtyas** designed the research methodology, ensured the suitability of the analytical approach, and managed the validation process of the framework through case studies and comparative evaluations. **Galih Prakoso Rizky A** contributed to data processing, empirical analysis, and the creation of visual representations of the research framework, as well as drafting the results and discussion sections. Meanwhile, **Hengki Tamando Sihotang** concentrated on formulating the practical implications and organizational adoption recommendations, developing mathematical modeling, and refining the conclusion while maintaining academic and linguistic consistency throughout the manuscript.

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**COMPETING INTEREST**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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