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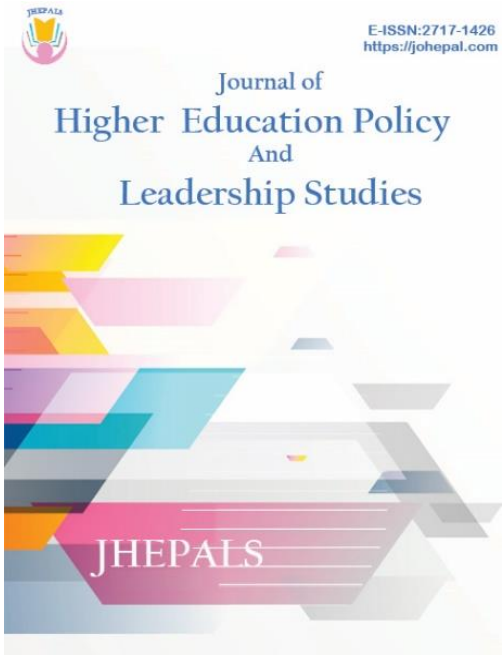

Simulating Digital Equity and Quality Gaps Associated with Digital Transformation in Higher Education

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Abstract

Despite a decade of sustained investment in digital technologies, Higher Education Institutions (HEIs) continue to show uneven progress in access and educational quality. This paper analyses the structural conditions behind the gap between Digital Transformation (DT) and educational outcomes through a System Dynamics model that connects technological investment, faculty training, organisational culture, and social equity. Five scenarios were simulated for 2025–2035, varying investment, obsolescence, and equity; the model was parameterised with Colombian data and validated through structural, dimensional, extreme-condition, and sensitivity tests. The results suggest that DT depends less on maximising infrastructure investment than on coordinating institutional conditions. A scenario combining moderate investment with stronger equity reached about 90% of the educational quality obtained under maximal investment, with roughly one-third of the infrastructure. Infrastructure obsolescence and the loss of relevance of faculty digital skills followed different trajectories and therefore call for separate policy responses. Equity acts as a precondition for effective DT rather than a by-product: without equitable access, investment and training do not translate into educational opportunities at the scale policy agendas expect. The study offers a transferable System Dynamics model that other institutional contexts can re-parameterise with their own data.

Keywords: Digital Transformation; System Dynamics Modelling; Higher Education; Digital Divide; Educational Equity; Educational Quality

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Introduction

Digital Transformation (DT) refers to the organisational change that results from the adoption and integration of emerging technologies into institutional operations (Tang, 2021). In higher education, it has evolved from a peripheral modernisation initiative into a strategic agenda that reshapes how universities teach, manage information, and engage with students (Gong & Ribiere, 2021; Rivera-Gutiérrez et al., 2024). The pandemic forced years of institutional adaptation into months. It also made visible a persistent gap between the technologies institutions deploy and the access and educational quality that students receive (Ramírez-Montoya et al., 2022; Chinkes & Julien, 2019; MEN, 2022).

This gap cannot be understood solely in technological terms. Lustosa Rosario et al. (2021) identify four recurrent barriers across Latin America and the Caribbean: limited rural connectivity, weak interoperability between institutional systems, insufficient staff training, and the absence of clear policies for integrating technology into teaching practices. These barriers are intensified in unequal societies, where the digital divide largely mirrors existing socioeconomic inequalities (González Ciriaco, 2024). Colombia illustrates this pattern clearly. In 2023, internet access reached 63.9% of households nationwide; however, coverage varied substantially, ranging from 70.5% in municipal centres to 41.4% in dispersed rural areas. Among households without internet service, 49% identified cost as the principal constraint (DANE, 2024). These disparities have direct implications for higher education, where access to degree programmes increasingly depends on reliable connectivity, access to digital devices, and institutional capacity to integrate both effectively.

Research on DT in higher education has developed along five main lines. The first examines institutional digital maturity (Fernández et al., 2023; Nieto-Taborda & Luppicini, 2025). The second proposes conceptual models that integrate vision, organisational culture, infrastructure, training, and community engagement (Restrepo Carvajal & Gómez Arenas, 2022; Alenezi, 2021). A third line focuses on perceptions and adoption processes, documenting persistent gaps in digital competencies between students and faculty members (Nguyen-Anh et al., 2023; Viñoles-Cosentino et al., 2022; Alhubaishy & Aljuhani, 2021). The fourth applies System Dynamics to specific educational challenges, including student retention, academic performance, and resource sharing (Guzmán Rincón & Barragán, 2022; Keith et al., 2024; Yang & Zhao, 2017). Finally, a fifth line of research connects DT with organisational innovation and social justice (Pérez, 2022; Xia et al., 2018).

Despite these advances, the literature has yet to connect these strands through an explicit feedback-based perspective. Most studies rely on cross-sectional surveys or case studies (Alenezi, 2021; Levano-Francia et al., 2019), which identify barriers and outcomes but offer limited explanation of how investment, training, and organisational culture interact non-linearly over time, or of why infrastructure obsolescence and faculty skill obsolescence may diverge under similar policy interventions. Existing simulation studies also analyse access, quality, and equity as separate dependent variables rather than as interdependent outcomes produced by the same system (Yang & Zhao, 2017; Keith et al., 2024).

This paper analyses the structural conditions that determine the gap between DT and educational outcomes in Higher Education Institutions (HEIs). The argument is developed through a System Dynamics model simulated over a ten-year horizon (2025–2035) across five policy scenarios, parameterised and validated with Colombian data but transferable in

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its structure to other higher education systems. The model shows that coordinated action across investment, equity, and faculty development outperforms strategies built around any single lever, and it offers a feedback-based explanation for the limited reach of infrastructure-centred reforms. Beyond this contribution to policy, the model brings together strands of research that have remained disconnected and illustrates how simulation can support decision-making in complex educational systems.

The remainder of the paper is organised as follows. The next section develops the conceptual framework. The Methodology section describes the system boundary, the causal-loop and Forrester diagrams, and the validation procedures. The Results section presents the simulation outcomes across the five scenarios, and the Discussion examines their practical and theoretical implications, limitations, and directions for future research. The Conclusions section summarises the main contributions of the study.

Conceptual Framework

Digital Transformation: Technology, People, and Organisational Culture

DT is understood as the adoption of digital tools and as a technology-driven process of organisational change that reshapes how institutions create value (Gong & Ribiere, 2021). The concept remains contested because the same term is often used to describe both incremental upgrades to learning management systems and broader institutional reorientations affecting the university mission itself (Fleaca et al., 2022). Castro Benavides et al. (2022) and Gkrimpizi et al. (2024) draw a productive distinction between these processes: digitalisation improves existing operations, whereas DT redefines what the institution does and the purposes it serves. Although both processes coexist in most HEIs, the latter is more closely associated with sustained improvements in access and educational quality.

In HEIs, DT develops through three interdependent domains: technology, people, and organisational culture (Alenezi, 2021; Levano-Francia et al., 2019; Kammerer David & Murgas Téllez, 2024). Infrastructure alone does not improve teaching if faculty lack the training required to use it effectively. Likewise, training initiatives tend to lose momentum in organisational environments that do not support or reward innovation. At the same time, a culture oriented towards innovation cannot be sustained without continued investment. Restrepo Carvajal and Gómez Arenas (2022) propose a model of DT in HEIs structured around four dimensions: installed technological capacity, digital culture, industry–university–state relations, and institutional and regional leadership. The model is complemented by cross-cutting attributes such as adaptability, flexibility, and relevance, which together reflect the degree of alignment between these domains. García-Peñalvo (2021) similarly describes DT as a sequence of coordinated changes involving institutional culture, staff development, and technological infrastructure.

Two processes of depreciation complicate this dynamic, although the literature frequently conflates them. The first is technological obsolescence: the gradual degradation of digital infrastructure, platforms, and systems over time. Infrastructure depreciates regardless of usage intensity, although the pace of deterioration depends on maintenance practices and on how deeply technologies are embedded within institutional routines (Fernández et al., 2023). The second process is faculty outdatedness, that is, the progressive

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loss of relevance of faculty digital competencies (Levano-Francia et al., 2019; Alenezi, 2021). Its rhythm depends on context: under relatively stable conditions, digital skills erode gradually through disuse and the normal turnover of technological practices; under accelerated technological change, the same competencies lose relevance more rapidly because the technological frontier evolves faster than professional adaptation (Prakash, 2024). When institutions invest heavily in platforms and digital infrastructure without proportional investment in faculty development, the gap between technological capacity and pedagogical use widens (Ramírez-Montoya et al., 2022). Levano-Francia et al. (2019), Alenezi (2021), and Prakash (2024) describe this dynamic as a technology–skill gap acceleration mechanism. Although obsolescence and outdatedness interact, they remain conceptually distinct: the former concerns hardware and software, the latter human capital.

Outcomes and Contextual Conditions: Access, Quality, and Equity

The first dimension is access. In higher education, access means the possibility of students to enrol, remain, and benefit from digital education, not just the formal availability of programmes or platforms. It depends on enrolment opportunities, retention conditions, and the availability of digital infrastructure at the student level (Ramírez-Montoya et al., 2022). Evidence from Latin American higher education systems shows that access remains uneven across regions, socioeconomic groups, and modalities of study, with the rural-urban divide and household connectivity as persistent barriers (Vovchasta et al., 2024). The expansion of digital education during the post-pandemic period has made these inequalities more visible without reducing them (Dhawan, 2022).

The second dimension is educational quality. In this context, it extends beyond test performance or accreditation indicators. It includes competencies for lifelong learning and critical thinking (Kayyali, 2023; Gupta, 2021), student satisfaction with academic and administrative services (Castro Benavides et al., 2022; Dhawan, 2022), curricular relevance to labour-market demands (Alenezi & Akour, 2023), and the institutional capacity to provide inclusive, student-centred learning environments (Camilleri, 2021). Bitar and Davidovich (2024) argue that coherent DT can foster pedagogical innovation and broaden educational access, improving both quality and equity. Post-pandemic evidence is more mixed. Lundberg and Stigmar (2024) report that faculty associate DT with greater methodological openness and flexibility for students but also identify reduced institutional support and emotional fatigue linked to continuous adaptation.

The third dimension is equity. Duk and Murillo (2024) observe that higher education is one of the social spaces where structural inequalities become most visible. Ensuring equitable access therefore requires that students can benefit from digital education regardless of socioeconomic status, gender, geographic location, or disability (Matsieli & Mutula, 2024). Equity is an outcome of investment and a prior condition that shapes whether investment translates into meaningful access. Evidence from rural and crisis-affected contexts confirms this: unequal access to digital devices, connectivity, and stable infrastructure shapes who uses the technologies institutions provide (Vovchasta et al., 2024; Clemons & Jance, 2024).

The literature also identifies contextual conditions that influence these relationships outside closed feedback loops. These include governance capacity, stakeholder engagement, digital trust, and readiness for organisational change (Prakash, 2024;

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Deichakivska et al., 2024; Gkrimpizi et al., 2023; Vovchasta et al., 2024; Yaseen et al., 2025). Investment strategies produce different institutional trajectories depending on the degree of participatory governance and the level of trust that faculty and students place in the technologies adopted. These conditions remain outside the scope of the present model, which focuses on the feedback structure linking four core processes: investment, training, organisational culture, and equity.

Maturity models and service-quality frameworks often treat access, quality, and equity as separate variables, not as interconnected outcomes of a shared dynamic structure. The following section presents a model that conceptualises these dimensions as outputs of an integrated feedback system.

Research Methodology

System Dynamics is a modelling approach developed to study systems with feedback loops, accumulations, and time delays (Sterman, 2000; Bala et al., 2017). It is well-suited to studying DT in HEIs because the relevant variables (investment, training, organisational culture, equity, and infrastructure) interact non-linearly: they accumulate, deteriorate, and interact through reinforcing and balancing processes over periods extending beyond a single academic year. System Dynamics also enables the simulation of prospective scenarios under different institutional and policy conditions, which helps identify leverage points and structural constraints that are difficult to observe with cross-sectional data (Bianchi & Salazar Rua, 2022; Bianchi, 2016).

Study design

The study is applied, exploratory, and prospective (Creswell, 2009). The purpose of this study is to analyse the structural conditions that determine the gap between digital implementation and educational outcomes in higher education institutions through the development and validation of a System Dynamics model. The model simulates alternative institutional and policy scenarios and identifies the conditions under which the gap narrows or widens (Martín González, 2022). The study followed a mixed-methods design with qualitative and quantitative System Dynamics tools across four stages.

First, the system boundary was defined from the conceptual framework developed before and from Colombian national policy reports, which identified the relevant actors, variables, and exclusions. Second, causal loop diagrams were developed to represent reinforcing and balancing feedback structures and to formulate dynamic hypotheses about long-term system behaviour. Third, the quantitative model was implemented in Vensim® PLE software (version 10.5.0), with variables organised as stocks, flows, and auxiliary elements, following previous applications of System Dynamics in educational contexts (Yang & Zhao, 2017; Keith et al., 2024; Guzmán Rincón & Barragán, 2022). Fourth, the model underwent four validation tests: structural review, dimensional consistency, extreme-condition testing, and sensitivity analysis.

The simulation horizon covered ten years (2025–2035) with annual time steps. This window allows medium-term effects to become visible while keeping the simulation within the reliability of the parameter estimates. Five scenarios were then simulated and compared with the baseline trajectory, following Bala et al. (2017) and Aracil (1995).

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System Boundary and Transferability

The unit of analysis is the set of systemic structures connecting the implementation of digital technologies with educational access and quality in higher education institutions. The model is conceptually general (its feedback loops and variables apply to higher education systems in general), but its parameterisation and validation are based on Colombian data (Landriscina, 2013). The model's structure is transferable because the core processes it represents (investment, training, organisational culture, equity, and infrastructure) appear in HEIs undergoing DT across national contexts. Parameter values, however, depend on context. Institutions in other settings can adapt the model using their own data on household connectivity indicators, faculty training rates, or infrastructure depreciation estimates, without altering its structural design. Transferability therefore refers to the feedback structure, not to the numerical values, which is consistent with the use of System Dynamics in policy-oriented applications (Bianchi, 2016).

The system involves several stakeholders: students, faculty, administrators, institutional managers, policymakers, regulatory agencies, technology providers, and the broader socioeconomic environment. Each shapes the investment, adoption, or impact of digital technologies. Model parameterisation drew on national data sources (DANE, 2024, for household and territorial connectivity; Ministry of Education, MEN, 2022, for enrolment data and policy targets) and on peer-reviewed research on DT in Latin American higher education institutions. The model is calibrated at the national aggregate level, not for any individual HEI.

Causal Loop and Forrester Diagrams

The model variables include technological investment, faculty training, organisational culture, pedagogical design, and access to digital infrastructure. Causal loop diagrams were constructed to represent two forms of feedback: reinforcing loops, in which changes intensify one another, and balancing loops, which stabilise system behaviour. This diagram helps formulate dynamic hypotheses about how variables interact over time and where leverage points may exist in the system (Bala et al., 2017; Aracil, 1995).

A Forrester diagram was then developed for quantitative simulation. The model has three categories of variables. Stocks represent accumulations such as educational quality or digital infrastructure. Flows represent rates of change such as annual investment or student dropout. Auxiliary variables, such as student satisfaction and institutional support, link stocks and flows. The complete set of equations, and parameter values is presented in Table 1.

Model validation

The model was validated through a set of procedures recommended by Sterman (2000) and Bala et al. (2017): a structural review, a check of dimensional consistency, extreme-condition tests, sensitivity analysis.

The structural review examined whether the causal relationships in the model were consistent with the literature on DT in higher education and with the Colombian institutional context. Each relationship between variables was reviewed against published evidence and revised iteratively during model construction.

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Dimensional consistency was verified across all equations. Stocks were expressed in their natural units (students, infrastructure units, training units, and dimensionless indices for culture and equity), flows in units per year, and auxiliary variables either in those units or as bounded indices within the interval [0,1].

Extreme-condition tests evaluated model behaviour under boundary parameter values. When investment was reduced to zero, infrastructure declined towards its lower bound and educational quality deteriorated. When the obsolescence rate reached its maximum, infrastructure collapsed within the simulation period.

Sensitivity analysis was conducted on two parameters: the investment policy coefficient (baseline = 0.37) and the obsolescence rate (baseline = 0.75). Each parameter was perturbed by ±10% relative to its baseline, and the mean absolute deviation from the baseline trajectory was calculated for four output variables: Social equity, digital infrastructure, learning outcomes, and professor's training in digital skills.

Model parameters were calibrated at the national aggregate level rather than for any individual institution, following a stylised approach in which values were adjusted to reproduce plausible national-level patterns reported in the data sources cited above.

Results

The results are presented in three parts. The first part describes the feedback structure behind the gap between technological implementation and educational outcomes. The second part translates this structure into a quantitative model through the Forrester diagram. The third part examines the behaviour of the principal variables across five simulated scenarios over the 2025–2035 period.

Causal Loop Diagram

The causal-loop analysis identifies six feedback loops within the system: four reinforcing (R1–R4) and two balancing (B1–B2). Reinforcing loops capture cumulative interactions among investment, training, organisational culture, equity, and learning outcomes. Balancing loops represent the structural constraints linked to infrastructure obsolescence and the loss of relevance of faculty digital competencies. Figure 1 presents the complete diagram.

R1 — Equity and learning outcomes. The equity dimension operates through a short reinforcing loop: Learning outcomes → Inclusive policies → Social equity → Institutional support → Learning outcomes.

Higher Learning outcomes sustain Inclusive policies, which raise Social equity. Social equity then strengthens Institutional support, which in turn feeds back into Learning outcomes (Duk & Murillo, 2024; Matsieli & Mutula, 2024). R1 shows that equity policies cannot be treated as compensatory additions to digital strategies; they are part of the same feedback structure that produces educational outcomes.

R2 — Culture and pedagogical use. Organisational culture and pedagogical practice reinforce each other through faculty development: Organisational culture of innovation → Professor's training in digital skills → Improvements through technological use → Organisational culture of innovation.

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A culture oriented towards innovation sustains the digital training of faculty, which in turn enables Improvements through technological use. The use of technology in teaching feeds back into the institutional culture, consolidating practices that support further training (Alenezi, 202; Restrepo Carvajal & Gómez Arenas, 2022). R2 helps explain why institutions with comparable financial resources may produce different educational outcomes: the culture–training–practice loop operates with relative autonomy from investment levels.

R3 — Annual training and learning outcomes. Investment translates into educational gains primarily through faculty development: Learning outcomes → Inclusive policies → Social equity → Institutional support → Investment in digital technologies → Annual training → Professor's training in digital skills → Improvements through technological use → Learning outcomes.

This is the principal reinforcing engine of the system. The institutional capacity built through training accumulates over time, and a delay is included between Annual training and Professor's training in digital skills because participation in training programmes does not translate immediately into consolidated competencies. Previous research suggests that the incorporation of new pedagogical practices typically takes one to two years (Sterman, 2000; Levano-Francia et al., 2019).

R4 — Investment and outdatedness. Investment also operates by reducing the rate at which faculty competencies lose relevance: Learning outcomes → Inclusive policies → Social equity → Institutional support → Investment in digital technologies → Outdatedness (−) → Professor's training in digital skills → Improvements through technological use → Learning outcomes.

The negative sign on the link Investment in digital technologies → Outdatedness reflects the operationalisation of Outdatedness as a saturation function: sustained investment reduces the rate of skill obsolescence. R4 reinforces R3 when investment is coordinated with training but produces tension when investment expands more rapidly than the institutional capacity to renew faculty competencies.

B1 — Obsolescence. Infrastructure depreciates regardless of usage intensity: Digital infrastructure → Obsolescence → Digital infrastructure (negative).

The rate of Obsolescence varies with maintenance practices and institutional adaptation, but the loop itself reflects a structural condition: any stock of infrastructure deteriorates and requires sustained investment to remain stable. B1 explains why short-term investment programmes lose effectiveness when they are not renewed.

B2 — Outdatedness. The second balancing loop concerns the loss of relevance of faculty digital competencies: Professor's training in digital skills → Outdatedness → Professor's training in digital skills (negative).

Outdatedness is operationalised through a saturation function of investment. Under conditions of sustained Investment in digital technologies, the rate of Outdatedness decreases and the institutional capacity for skill renewal is preserved. Under low or collapsing investment (as in Simulation 3 below), the same mechanism produces a sharp rise in Outdatedness because the institutional environment no longer sustains renewal. The richer dynamic described in the literature, in which rapid technological change accelerates the loss of relevance even when investment grows, is acknowledged conceptually but lies outside the present operationalisation.

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Architecture of the System

The six loops describe a system with four reinforcing engines and two structural constraints. R1 operates as a short equity-quality cycle; R2 sustains the culture–training–practice triangle with relative autonomy from investment; R3 and R4 represent the two long routes through which investment shapes outcomes (training and outdatedness, respectively). B1 and B2 represent persistent sources of structural friction: infrastructure deteriorates over time, and faculty competencies lose relevance unless investment sustains their renewal.

R3 and R4 share their initial segment (Learning outcomes → Inclusive policies → Social equity → Institutional support → Investment in digital technologies) and diverge in how investment reaches Professor's training in digital skills. R3 operates through Annual training, while R4 operates through the reduction of Outdatedness. When investment is coordinated with training, R3 and R4 reinforce each other. When investment expands without corresponding training, R4 dominates: investment reduces Outdatedness on paper but does not produce a parallel increase in active competencies. This asymmetry helps explain why infrastructure-centred digital strategies frequently fail to produce the educational gains expected from them.

Three contextual conditions (governance capacity, digital trust, and readiness for change) influence the intensity of these loops without being part of them. Higher levels of governance coordination and stakeholder engagement strengthen R1–R4 and partially offset the effects of B1 and B2. These conditions are acknowledged but remain outside the present model to preserve analytical focus.

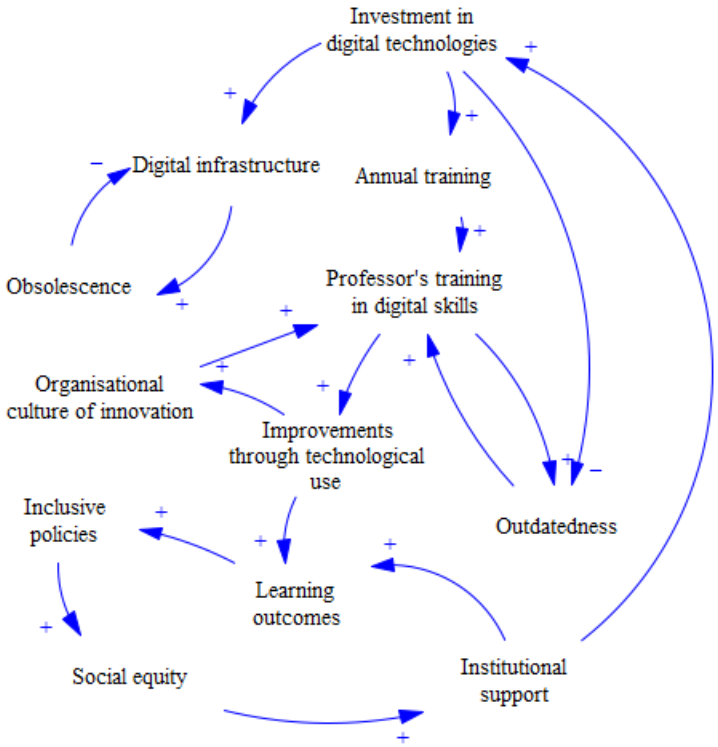

Figure 1. Feedback structure of DT in HEIs

[Sources: Elaborated by the authors based on Ainscow (2016), Cañon Ospina et al. (2024), Gil-Fernández and Calderón-Garrido (2023), Jacovkis et al. (2024), Area-Moreira et al. (2020), Peirats Chacón et al. (2022), and Selwyn (2004).]

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Forrester Diagram

The Forrester diagram (Figure 2) translates the causal-loop structure into a quantitative model that can be simulated over time. The model is organised around six stocks, eleven flows, and a set of auxiliary variables that mediate or modulate the relationships between them. The variables and equations are presented in Table 1.

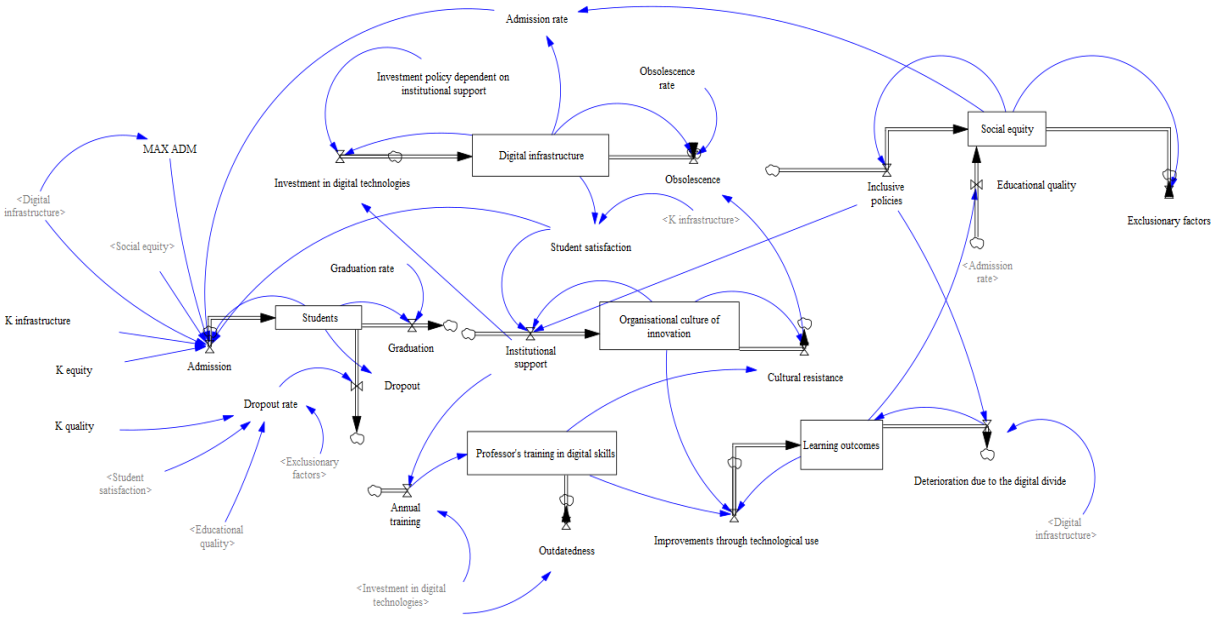

Figure 2. Stock-and-flow structure of the DT model in HEIs.
[Sources: Elaborated by the authors.]

Six stocks form the core of the model: Digital infrastructure, Professor's training in digital skills, Organisational culture of innovation, Learning outcomes, Social equity, and Students. Each stock has at least one inflow and one outflow. Digital infrastructure accumulates with Investment and declines with Obsolescence. Professor's training accumulates with Annual training and decreases with Outdatedness. Learning outcomes improve with the pedagogical use of technology and deteriorate with the effects of the digital divide. The Students stock increases with admission and decreases with Dropout and Graduation. Organisational culture and Social equity follow the same logic, with inflows and outflows for institutional support, cultural resistance, inclusive policies, and exclusionary pressures.

Two notational conventions need clarification. First, the model uses K-values (K_infrastructure = 100, K_quality = 1000, K_equity = 1) as benchmark scales for cross-scenario comparison. These reference levels keep dimensionless indices on a consistent numerical range. Second, several auxiliary variables are bounded within the interval [0,1] through MIN–MAX operators. These bounds preserve the meaning of variables such as Student satisfaction, Inclusive policies, and Admission rate, which represent proportions or indices and not unbounded quantities.

The model represents the two depreciation processes as distinct variables. Obsolescence applies to digital infrastructure and is modelled as a first-order decay process whose rate depends on the existing infrastructure stock, the obsolescence-rate parameter,

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and the level of cultural resistance to digital change. Outdatedness applies to faculty digital competencies and follows a saturation function of investment, 100 / (1 + Investment in digital technologies). In this version of the model, outdatedness is represented as a simplified inverse function of institutional investment, assuming that sustained investment signals institutional commitment to renewal. This formulation captures a necessary condition for faculty skill renewal but does not yet represent the acceleration of skill obsolescence under rapid technological change. This limitation is addressed later as a future extension of the model.

Two implications follow from this formulation. When investment levels are high, outdatedness approaches zero asymptotically: faculty remain exposed to opportunities for renewal. When investment levels are low, outdatedness approaches its upper bound of 100: faculty competencies lose relevance because the institutional environment does not prioritise renewal. The simulations show that high investment alone is not the most efficient route to educational quality. Comparable outcomes can be reached at much lower infrastructural cost when investment, training, and equity move together.

Table 1 presents the full specification of the model, with variables, equations, categories, units, and brief interpretive descriptions. Stocks are represented as integrated quantities, flows as rates of change in annual units, and auxiliary variables either keep those units or operate as bounded indices within the interval [0,1]. Parameter values were defined using a combination of Colombian aggregate data, literature-based assumptions, and internal calibration. Observable variables, such as connectivity and enrolment indicators, were informed by national data sources, while non-observable behavioural and policy parameters were specified according to the conceptual framework and adjusted to generate plausible baseline behaviour. These values should therefore be interpreted as modelling assumptions for scenario comparison, not as direct empirical estimates or forecasts.

Table 1.
Variables, equations, units, and parameter specifications of the System Dynamics model.

Variable	Equation	Interpretation
Admission	MAX(0.01, MIN(MAX_ADM, Students × Admission rate × (Digital infrastructure / K_infra) × (Social equity / K_equity) × Student satisfaction))	Admitted students, constrained by institutional capacity, infrastructure, equity, and satisfaction.
Admission rate	MIN(1, MAX(0.01, MIN(Digital infrastructure, Social equity)))	Admission rate index.
Annual training	MIN(1000, MAX(0.01, Institutional support × Investment in digital technologies))	Annual faculty training.
Cultural resistance	1 − 1/MAX(0.1, MAX(0.01, Organizational culture of innovation) × MAX(0.01, Professor's training in digital skills))	Cultural resistance to DT.
Deterioration due to the digital divide	1 − 1/MAX(0.1, MAX(0.01, Digital infrastructure) × MAX(0.01, Inclusive policies))	Quality deterioration driven by the digital divide.
Digital infrastructure	INTEG(Investment in digital technologies − Obsolescence, 6230)	Cumulative digital infrastructure.
Dropout	Dropout rate × Students	Students dropping out.
Dropout rate	MIN(1, MAX(0.1, Exclusionary factors × 0.3 + (1 − Educational quality/K_quality) × 0.4 + (1 − Student satisfaction) × 0.3))	Dropout rate driven by exclusion, quality, and satisfaction.

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Educational quality	Learning outcomes × 0.47	Quality scaled from learning outcomes.
Exclusionary factors	MIN(1, MAX(0, 1 − Social equity × 0.36))	Factors restricting educational inclusion.
Graduation	Graduation rate × Students	Graduating students.
Graduation rate	0.47	Proportion of students graduating.
Improvements through technological use	Organizational culture × 0.2 + Professor's training × 0.3 + 0.17 × Learning outcomes	Quality gains from pedagogical use of technology.
Inclusive policies	Social equity × 0.85	Inclusive policies driven by equity level.
Institutional support	MIN(1, MAX(0, (Inclusive policies + Organizational culture + Student satisfaction)/3))	Average institutional support.
Investment in digital technologies	MIN(1000, MAX(0.01, Digital infrastructure × Investment policy × Institutional support))	Annual investment in digital technologies.
Investment policy dependent on institutional support	0.37 (baseline)	Investment policy scaling parameter.
Learning outcomes	INTEG(Improvements through technological use − Deterioration due to the digital divide, 358)	Cumulative learning outcomes.
MAX_ADM	500 + 0.5 × Digital infrastructure	Maximum Admission capacity.
Obsolescence	Digital infrastructure × Obsolescence rate × Cultural resistance	Depreciation of digital infrastructure.
Obsolescence rate	0.75	Annual obsolescence rate.
Organizational culture of innovation	INTEG(Institutional support − Cultural resistance, 0.82)	Cumulative culture oriented to innovation.
Outdatedness	100/(1 + Investment in digital technologies)	Faculty outdatedness, modeled as a saturation function of investment.
Professor's training in digital skills	INTEG(Annual training − Outdatedness, 64)	Cumulative faculty training.
Social equity	INTEG(Educational quality + Inclusive policies − Exclusionary factors, 0.65)	Cumulative Social equity index.
Student satisfaction	MIN(1, MAX(0, Digital infrastructure × 0.35 / K_infrastructure))	Student satisfaction.
Students	INTEG(MAX(0.01, Admission − Dropout − Graduation), 8700)	Total students in the system.

Scenario Simulation: Digital Divide and Educational Outcomes

Five scenarios were simulated over the 2025–2035 period and compared against the baseline trajectory. The scenarios cover five contrasting policy configurations: status quo, intensive technological investment, accelerated infrastructure obsolescence, structural inequity, and coordinated investment combining moderate investment with stronger equity conditions.

Simulation 1: Reference model (baseline). Represents the status quo, with no changes in institutional behaviour or policy. All parameters retain their baseline values.

Simulation 2: High sustained investment. Investment policy coefficient = 0.9. Represents an institution prioritising maximal digital investment.

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Simulation 3: Accelerated obsolescence. Obsolescence rate = 0.9. Represents a context characterised by rapid technological degradation resulting from intensive use, inadequate maintenance, or accelerated technological change across the sector.

Simulation 4: Low Social equity. Initial Social equity = 0.20. Represents an institution operating under conditions of pronounced inequality, with limited capacity to reach historically underserved populations.

Simulation 5: Coordinated investment. Investment policy coefficient = 0.6 and initial Social equity = 0.85. Represents an institution combining moderate but sustained digital investment with strengthened equity conditions. Unlike Simulation 2, this scenario does not maximise infrastructure expansion; unlike Simulation 4, it does not neglect equity conditions. Instead, it coordinates both policy dimensions simultaneously.

Table 2 presents the final values (year 2035) for the principal output variables across the five scenarios.

Access: Simulation 2 produces the largest increase in admissions (1,167 students per year compared with 518 in the baseline scenario), because infrastructure expansion reinforces educational opportunity. Simulation 5 increases admissions to 727 students, a 40% rise over the baseline with a more moderate investment strategy. Simulation 3 records the lowest admissions because accelerated technological degradation weakens the reinforcing effects of infrastructure development. Total student enrolment remains close to 8,700 across all scenarios because the system absorbs admission gains through graduation and dropout flows.

Educational quality: The simulations show a contrast between investment intensity and educational-quality outcomes. Simulation 2 reaches the highest level of educational quality (10,740) through maximal infrastructure investment. Simulation 5 reaches 9,639, about 90% of the quality reached in Simulation 2, with much lower infrastructure (455 against 1,334) and a more moderate investment strategy. Within the model, Simulation 5 shows a higher educational-quality-to-infrastructure ratio than Simulation 2, suggesting that coordinated strategies may be more efficient than infrastructure-maximising strategies. This is the principal finding of the simulation: coordinated action across two policy dimensions produces educational-quality outcomes comparable to those of maximal single-dimension investment, at a fraction of the infrastructural cost.

Simulation 1 stabilises at 6,961, while Simulation 4 reaches 6,654, slightly below the baseline despite identical investment parameters. The decline occurs because reduced initial equity propagates through the equity–quality feedback loop and limits educational outcomes over time. Simulation 3 records the lowest quality level (5,142), a situation in which infrastructure obsolescence advances faster than institutional investment.

Digital divide: The infrastructure trajectories show the structural costs of each policy configuration. Simulation 2 ends with infrastructure at 1,334 units and obsolescence at 1,000, a high-volume and high-cost configuration in which technological renewal barely compensates for degradation. Simulation 5 ends with infrastructure at 455 units and obsolescence at 341, a leaner configuration that nevertheless sustains educational quality close to the level reached in Simulation 2. Simulation 3 represents the opposite extreme: infrastructure declines to 2.04 units and obsolescence to 1.76, and the system reorganises around a degraded equilibrium with much lower educational quality. Faculty outdatedness

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remains low across the four scenarios with normal or high investment levels (between 0.099 and 6.96). This reflects the model's structure: sustained investment acts as a proxy for institutional commitment to faculty skill renewal. Simulation 3 produces the highest outdatedness value (57.86) because infrastructural collapse removes the conditions that sustain faculty skill renewal.

Table 2.
Final values of key system outputs across simulated scenarios (2035).

Sim	Admission	Students	Educational quality	Learning outcomes	Digital infrastructure	Obsolescence	Outdatedness
1	518.05	8,700	6,961.62	14,812	36.10	27.06	6.96
2	1,166.79	8,700	10,740.50	22,805	1,333.59	1,000.03	0.099
3	500.98	8,700	5,142.56	10,942	2.04	1.76	57.86
4	518.10	8,700	6,654.86	14,159	36.20	27.13	6.94
5	727.41	8,700	9,639.16	20,509	454.84	341.05	0.37

Sensitivity Analysis

Model robustness was evaluated through a local sensitivity analysis on two parameters: the investment policy coefficient (baseline = 0.37) and the obsolescence rate (baseline = 0.75). Each parameter was perturbed by ±10% from its baseline, and the mean absolute deviation of four output variables (Social equity, Digital infrastructure, Learning outcomes, and Professor's training in digital skills) was calculated from the baseline trajectory. Figure 3 presents the results.

The analysis revealed three main patterns. First, the obsolescence rate has the strongest influence across all four output variables. A ±10% variation in the obsolescence rate produces deviations between 1.5 and 4.3 times greater than the same variation in the investment policy coefficient. This is consistent with the model's structure: obsolescence acts directly on the outflow of the infrastructure stock, while investment reaches the same stock through several auxiliary variables.

Second, the system shows asymmetric responses to positive and negative perturbations. For Social equity, a 10% increase in the obsolescence rate produces a mean absolute deviation of 1,587, against 736 under a 10% reduction, a 2.2-fold asymmetry. Learning outcomes and Professor's training in digital skills show comparable patterns. This asymmetry reflects the non-linear behaviour of the system: stocks accumulate gains and losses at different rates because the auxiliary variables that regulate the flows include MIN–MAX bounds and proportional relationships that behave differently under expansion and contraction.

Third, the direction of the responses follows the structural logic of the model. The investment policy coefficient affects Learning outcomes and Professor's training in the same direction: investment increases improve both variables. Obsolescence rate increases reduce them. Together, these two parameters represent the central tension in the system: investment builds institutional capacity over time, while obsolescence erodes it. The balance between these opposing processes determines whether the system accumulates educational gains or reorganises around a degraded equilibrium. This interpretation is consistent with the central finding reported in the scenario simulation results: coordination

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across policy dimensions is more effective than maximisation of a single intervention because it manages the relationship between the two flows instead of intensifying one.

The model therefore remains robust under small perturbations of its critical parameters within the range covered by the five scenarios. Larger perturbations were not tested because the scenario design (particularly Simulations 2 and 3) already captures the boundary conditions of high and low parameter values. The qualitative ordering of outcomes also remained stable across all five simulations.

Figure 3. Sensitivity of key output variables to investment and obsolescence parameters.
*Note: Red bars represent negative perturbations; blue bars represent positive perturbations. Bar lengths show the mean absolute deviation between the perturbed run and the baseline run.

Discussion

The simulations help explain why the gap in access and educational quality persists in higher education institutions despite more than a decade of digital investment (Ramírez-Montoya et al., 2022; MEN, 2022; Chinkes & Julien, 2019). The persistence of this gap has structural origins. It reflects the configuration of the system in which technology is implemented, where investment, training, organisational culture, and equity interact in ways that determine whether technological deployment translates into educational outcomes. The model produces three findings that challenge assumptions still present in policy discussions on DT.

The first finding concerns the relationship between investment intensity and educational quality. Simulation 2 reaches the highest level of educational quality, but only through infrastructure expansion (1,334) and an obsolescence level (1,000) that may be difficult to sustain over time and could exceed the institution's capacity to absorb technological change productively. Simulation 5 reaches an educational quality level of 9,639, about 90% of the outcome reached in Simulation 2, with infrastructure at 455. In proportional terms, coordinated policy intervention produces greater educational returns per infrastructural unit than maximal investment alone. Sterman (2000) and Bianchi (2016)

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make a comparable argument about strategic intervention in complex systems: the effects of policy depend less on the magnitude of intervention than on the feedback structures it activates. A moderate but coordinated strategy that combines investment and equity strengthens R1 (the equity–quality loop) and R3 (the annual-training loop) more effectively than a larger intervention concentrated on R4 (investment via outdatedness), where investment reaches faculty competencies only through the saturation function and not through active training.

The second finding concerns the role of equity within the system. Simulation 4 reduces the initial equity value from 0.65 to 0.20 and produces only limited variation in admissions, yet educational quality declines measurably (from 6,961 to 6,654). The effect appears modest in absolute terms, but its structural significance is considerable because equity operates upstream within the system. Simulation 5 shows the inverse relationship: raising initial equity to 0.85, combined with moderate investment, raises educational quality by 38% relative to the baseline and produces the second-highest quality outcome across all scenarios. DANE (2024) and Gil de Zúñiga et al. (2022) describe a similar pattern. Equity rarely generates immediate effects on access, which partly explains why it is often deprioritised in short-term planning. Over the medium term, it shapes the capacity of institutions to convert investment into educational outcomes. Equity-oriented policies therefore form part of the same structural process that produces educational quality, and operate as constitutive rather than compensatory.

The third finding concerns the joint behaviour of infrastructure obsolescence and faculty outdatedness across scenarios. The model represents both as forms of depreciation, but they respond to different stocks (infrastructure and trained faculty) and to different drivers, and they do not evolve in parallel. In Simulation 2, infrastructure renewal occurs at high volume (obsolescence flow = 1,000) while outdatedness remains near zero (0.099): sustained institutional commitment to digital investment supports continuous faculty renewal. In Simulation 3, infrastructure collapses (obsolescence = 1.76) and outdatedness rises to 57.86: the deterioration of infrastructure removes the institutional conditions that sustain skill renewal. Depreciation processes affecting infrastructure and human capital are coupled, yet they are not interchangeable. A strategy centred exclusively on infrastructure renewal does not automatically support faculty skill renewal, and the same limitation applies in the opposite direction. Fernández et al. (2023) and Ramírez-Montoya et al. (2022) warn against precisely this assumption, arguing that sustainable DT requires parallel attention to technological renewal and human capital development.

Conclusions

This study analyses the structural conditions that determine the gap between DT and educational outcomes in HEIs through the development and validation of a System Dynamics model. The model was parameterised using Colombian aggregate data and validated through structural consistency, dimensional consistency, extreme-condition testing, and local sensitivity analysis. It was then simulated over a ten-year horizon under five alternative scenarios. Three structural conclusions follow from the analysis.

First, the digital divide cannot be reduced to infrastructure alone. It is produced by the interaction between infrastructure, faculty development, organisational culture, and equity,

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and persists whenever those dimensions become disconnected. Second, coordinated intervention across policy dimensions produces more effective outcomes than maximising any single intervention. Moderate investment combined with stronger equity conditions generates educational-quality outcomes close to those produced by maximal investment, at a fraction of the infrastructural cost. Third, Social equity operates as a structural precondition for the productive deployment of investment. Where it is absent, investment fails to translate into access and educational quality at the scale commonly assumed in policy agendas.

The main contribution of this study is not the prediction of future values, but the formal representation of the feedback structure through which digital investment, equity, faculty development, and organisational culture jointly shape educational outcomes. The model provides a transferable structural framework that other higher education systems can re-parameterise with their own data, and a feedback-based perspective that complements linear interpretations of cause and effect. As Oliva (2019) notes, models of this kind should be understood as starting points for further inquiry.

Implications of Research

Practical Implications

Several priorities for HEIs and ministries of education follow from these findings. The most immediate is the design of coordinated investment strategies. Plans centred on infrastructure produce educational gains that are lower per unit of investment and harder to sustain. Investment plans should specify, from the outset, the proportion of resources directed to faculty development and to equity, treating these as integral components of the strategy and giving them the same status as the infrastructure component.

A complementary priority concerns governance and monitoring mechanisms that track the gap between intended and actual DT in real time. The simulations show that the same investment level can produce different institutional trajectories depending on how it is distributed and how it interacts with cultural, equity, and training conditions. In the absence of monitoring instruments that capture this distribution, institutions may report high investment indicators while educational outcomes stagnate.

Equity policies require a parallel rethinking. Given the upstream role of equity within the system, instruments such as admissions policies, financial aid, connectivity programmes, and support for underrepresented groups should be considered part of the DT strategy from the design stage, with the same priority assigned to budget allocation and to monitoring as the technological components receive.

Theoretical Implications

The most general contribution of the model is the integration of investment, training, organisational culture, equity, and educational outcomes within a single feedback structure. Existing studies typically address these dimensions separately, either through cross-sectional surveys or through case studies that describe their interaction in qualitative terms. The System Dynamics model presented here allows their interdependencies to be examined formally and over time.

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A second contribution lies in the conceptual distinction between infrastructure obsolescence and faculty outdatedness, which the literature often conflates. The two processes operate on different stocks, respond to different drivers, and exhibit different temporal dynamics. Treating them as distinct variables clarifies why infrastructure-centred strategies fail to support faculty skill renewal automatically and why coordinated strategies produce more sustainable outcomes.

The model also reframes equity as an upstream condition for DT. This reframing has analytical consequences. Equity ceases to be a variable that is optimised at the end of the DT process and becomes a structural condition that shapes how the process unfolds. This perspective opens space for further work on how institutional commitments to equity interact with technological and pedagogical processes over time.

Limitations and Future Research

Three limitations deserve explicit mention. First, the model is aggregated at the institutional level and does not capture heterogeneity across faculty, programmes, or student subgroups. Disaggregating the model to represent this heterogeneity, possibly through an agent-based extension focused on faculty decision-making, is a natural next step.

Second, the parameterisation uses Colombian data. The structural model transfers across higher education systems, but the specific values do not. Applying the model in other contexts requires re-parameterisation with local data. Comparative parameterisation across countries would also provide an empirical test of the model's transferability.

Third, the model represents outdatedness as a saturation function of investment, which captures one institutional mechanism (sustained investment as a proxy for renewal commitment) without representing the technology–skill gap acceleration mechanism documented in the literature (Levano-Francia et al., 2019; Alenezi, 2021). A more detailed formulation of faculty skill dynamics, including the explicit representation of acceleration effects under rapid technological change, is a clear extension of this work.

The model also focuses on four core processes (investment, training, culture, equity) and does not represent governance capacity, digital trust, or readiness for change as variables. These contextual conditions influence the loops described here without forming part of them, and their explicit modelling is a direction for future research.

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Human Participants

This study did not involve human participants. The model was parameterised using publicly available aggregate data (DANE, 2024; MEN, 2022) and published literature.

Originality Note

The authors confirm that the manuscript is their original work, and if others' works are used, they are properly cited/quoted.

Use of Generative AI/ AI-assisted Technologies Statement

The authors used generative artificial intelligence tools only to assist with language editing, stylistic revision, and the formatting of references according to APA style. All references were subsequently verified by the authors against the original sources. These tools were not used to generate substantive content, analytical ideas, or interpretations. All decisions regarding the study design, the construction and validation of the System Dynamics model, the simulations, the analysis, and the interpretation of findings remain the responsibility of the authors.

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