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A SYSTEMS DYNAMICS MODEL FOR STUDENT RETENTION AND GRADUATION EFFICIENCY IN TECHNICAL INSTITUTIONS

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Abstract

Technical and Vocational Education and Training (TVET) institutions in sub-Saharan Africa face a systemic challenge of high student dropout and low graduation efficiency, driven by interlocking dynamics of financial stress, inadequate academic support, misaligned employability expectations, and weak industry linkages. Traditional linear statistical models fail to capture the feedback-driven complexity of these interactions, which operate across multiple time scales and generate non-linear institutional behaviour. Objective: This study develops and validates a Systems Dynamics (SD) model to simulate the feedback interactions among dropout, retention, financial stress, academic support, and employability expectations in Kenyan TVET institutions, calibrated to empirical data from the TVET Authority (TVETA) and the Higher Education Loans Board (HELB), with the objective of identifying high-leverage policy interventions for improving graduation efficiency. Methods: A stock-and-flow SD model comprising five primary stocks (Enrolled Students, Retained Students, Dropout Students, Graduates, and Financial Stress Index) and twelve feedback loops — six reinforcing and six balancing — was developed using Forrester's system dynamics methodology. Model parameters were estimated from TVETA Annual Returns data (2018–2023), HELB sustainability reports, and published empirical literature on TVET dropout determinants. Structural validity was confirmed through dimensional consistency checks, extreme-condition tests, and behaviour reproduction against the documented dropout decline from 20.77% (2018) to 2.94% (2023). Three policy scenarios — financial support expansion (Policy A), academic quality and employability linkage (Policy B), and combined intervention (Policy C) — were simulated over a 10-year horizon (2018–2028). Results: The calibrated model reproduced the observed dropout trajectory with a Mean Absolute Percentage Error (MAPE) of 3.8%, confirming structural validity. Sensitivity analysis identified HELB financial coverage expansion (PRCC = −0.84) and industry–TVET employment linkage (PRCC = +0.79 for graduation rate gain) as the dominant leverage points. Policy C (combined) simulations project dropout rates declining to 1.2% by 2028 and graduation rates reaching 87.4%, compared with 3.1% and 72.6% respectively under the baseline. The financial stress feedback loop, operating with a time delay of approximately 1.8 years, is identified as the primary driver of dropout reinforcement. Conclusion: SD modelling reveals that TVET student attrition is a non-linear, feedback-driven phenomenon resistant to isolated single-domain interventions. Combined financial support and employability-linked academic quality programmes generate synergistic gains exceeding the sum of individual policy effects, demonstrating the existence of a positive reinforcing loop between retention and institutional reputation that policymakers must deliberately activate.

Keywords: Systems dynamics, student retention, TVET, dropout modelling, feedback loops, graduation efficiency, Kenya.

INTRODUCTION

Technical and Vocational Education and Training (TVET) institutions occupy a strategic role in national human capital development, particularly in sub-Saharan Africa where formal employment in skilled trade and technical sectors is chronically undersupplied relative to demand. Kenya's government, recognising this strategic imperative, enacted sweeping TVET reforms beginning with Sessional Paper No. 14 of 2012, targeting a 20 percent increase in enrolment by 2023, and intensified its commitment through the expansion of Higher Education Loans Board (HELB) access to TVET trainees from the 2018/2019 financial year. The results are quantifiable: national TVET enrolment grew from 116,564 in June 2018 to 265,095 in 2021/2022 — a 127 percent increase in four years — while the number of accredited TVET institutions grew by 16.7 percent to 2,289 between 2017 and 2018 alone (Mutua, 2020; Mujuri & Kathomi, 2025).

Yet enrolment expansion alone does not translate into graduation efficiency. The TVETA Annual Returns Report 2023 documents a national dropout rate of 20.77% in 2018 among National Polytechnics, declining to 2.94% by 2023, attributing the improvement primarily to HELB funding expansion (TVETA, 2024). While this decline is remarkable, it still implies that nearly 3 in every 100 enrolled trainees leave without completing their programmes annually, representing a significant loss of human capital investment. More critically, the 2023 graduation rate at the Kenya School of TVET (KS-TVET) was documented at 65% — meaning that 35% of enrolled students did not graduate in the expected cohort period (TVETA, 2024). The Kenya Manufacturing Association (KAM) concurrently estimated Kenya's youth unemployment rate at 39% as of 2021, while simultaneously reporting critical shortages of qualified technical personnel in manufacturing sectors (KAM, 2021). This paradox — of structural technical skills shortages coexisting with TVET dropout and underemployment — suggests a systemic misalignment between TVET programme delivery and labour market realities.

Understanding these dynamics requires a modelling approach capable of representing the interdependent, feedback-driven nature of the dropout-retention system. Standard regression models, while useful for estimating average treatment effects, are inherently static and linear, unable to capture the time-delayed, non-linear feedback loops through which financial stress amplifies dropout, dropout reduces institutional revenue, reduced revenue degrades academic quality, and degraded quality further elevates dropout. Systems Dynamics (SD) modelling, pioneered by Jay Forrester at MIT in the 1950s and extended extensively in educational and social policy contexts, provides precisely this capability (Forrester, 1961; Sterman, 2000). SD models represent systems as stocks (accumulated quantities), flows (rates of change), and feedback loops, generating dynamic simulation trajectories rather than static predictions.

Despite its demonstrated utility in higher education capacity planning — including enrolment management, faculty planning, and research output modelling (Savsar & Aldaihani, 2014) — SD modelling has been minimally applied to TVET student retention in the East African context. Existing studies of TVET dropout in Kenya and the broader region rely predominantly on cross-sectional surveys and qualitative institutional analyses, providing snapshots of causal determinants without modelling the dynamic propagation of these effects over time (Mujuri & Kathomi, 2025; TVETA, 2024; Muchira et al, 2023). This paper addresses that gap by developing, calibrating, and simulating a comprehensive SD model of TVET student retention dynamics in Kenya, grounded in verified empirical data and structured around the five key interaction domains identified in the literature: dropout, retention, financial stress, academic support, and employability expectations.

Literature Review

TVET Dropout: Prevalence and Determinants in Sub-Saharan Africa

Student dropout in TVET institutions is a multi-causal phenomenon shaped by financial, academic, social, and institutional factors operating at different levels of the educational system. The TVETA Annual Returns 2023 provides the most comprehensive publicly available data on Kenyan TVET dropout, documenting the dramatic decline from 20.77% (2018) to 2.94% (2023) across National Polytechnics, and attributing this primarily to the sharp growth in HELB-funded trainees from approximately 40,000 in 2018/2019 to 105,000 in 2019/2020 — a 162.5% increase in one financial year (TVETA, 2024). This natural experiment provides strong evidence for the causal role of financial support in reducing dropout, consistent with the broader regional literature.

Muchira et al. (2023), in their assessment of TVET institutions' curriculum alignment with labour market demands in Kenya, identified inadequate resources, outdated equipment, and minimal practical components as structural barriers to skills acquisition, directly affecting graduates' employability (Muchira et al, 2023). Kabiru et al. (2021) documented that low household income significantly contributed to higher dropout rates among Kenyan secondary and post-secondary students, with financial constraints operating through multiple pathways: inability to afford fees, materials, uniforms, and transport, as well as the competing opportunity cost of remaining in education versus immediate

income generation (Kabiru, Motungo, & Nzengya, 2021). The Gates Open Research study on TVET and labour market transitions in Kenya (2025) confirmed that despite high enrolment growth, concerns about post-graduation employability — particularly given Kenya's 39% youth unemployment rate — constitute a significant demand-side deterrent to TVET completion (KAM, 2021).

At the regional level, Mushi and Mtenzi (2020) in Tanzania and Alemu and Tadesse (2019) in Ethiopia documented that limited parental involvement, poor school infrastructure, and cultural-economic constraints compound financial barriers to TVET completion. The systemic nature of these interactions — where financial stress reduces engagement, reduced engagement impairs academic performance, impaired performance reduces motivation and increases the perceived cost-benefit ratio of dropout, and dropout itself reduces institutional revenue and thus the quality of academic support available to remaining students — characterises the dropout system as a classic reinforcing feedback loop (Farrell et al., 2021; Tadesse et al., 2021).

Systems Dynamics in Educational Modelling

System dynamics (SD), developed by Forrester (1961) and extended by Sterman (2000) in Business Dynamics, provides a mathematical framework for modelling the non-linear, time-delayed feedback processes characteristic of complex social systems (Forrester, 1961; Sterman, 2000). SD models are built from four primitive elements: stocks (state variables accumulating over time), flows (rates of change of stocks), converters (auxiliary variables computing intermediate quantities), and feedback loops (causal chains returning to their origin, either reinforcing [R] or balancing [B]). The core differential equation governing a stock S with inflow α and outflow β is:

$$dS/dt = \alpha(t) - \beta(t) \quad \ldots (1)$$

where the functional forms of α and β may depend non-linearly on S itself and on other stocks, creating the feedback structure. Time delays are introduced through pipeline or first-order exponential smoothing structures. Sterman (2000) demonstrates that counter-intuitive dynamic behaviours — including oscillation, exponential growth followed by collapse, and policy resistance — arise naturally from seemingly simple feedback configurations when time delays are present (Sterman, 2000). These behaviours are routinely observed in educational systems: for example, financial aid policy expansions generate a lag before dropout reductions become visible in institutional statistics, while improvements in graduate employment outcomes take time to propagate back as increased enrolment and reduced dropout through reputation effects.

Savsar and Aldaihani (2014) developed an SD model for higher education capacity planning at Bogazici University, demonstrating that SD models can faithfully reproduce historical enrolment and faculty dynamics while enabling scenario testing for policy interventions (Savsar & Aldaihani, 2014). Tadesse et al. (2021) applied SD in the context of educational learning environments, while the Social System Design Lab (2021) demonstrated the application of Causal Loop Diagrams to K-12 dropout dynamics (Tadesse et al., 2021). The Education Systems Dynamics literature (System Dynamics in Education Project, MIT) has formally mapped feedback structures in student progression, identifying the critical role of balancing loops in limiting dropout under adequate support conditions.

Financial Stress, Academic Support, and Employability as Feedback Drivers

Three domains emerge consistently from the literature as the primary feedback drivers of TVET dropout dynamics in the East African context. First, financial stress operates as the dominant reinforcing driver: TVETA's documentation of the HELB expansion's impact (dropout declining 87% over five years) represents perhaps the clearest natural experiment evidence available on the financial stress-dropout feedback loop in any African TVET context (TVETA, 2024). Second, academic support quality acts as a balancing feedback: institutions with higher instructor-to-student ratios, more experienced trainers, and more current equipment generate lower dropout rates (Muchira et al, 2023). TVETA data shows trainer qualifications in Kenya ranging from below-craft certificate to PhD, with 43.58% holding bachelor's degrees and only 0.68% holding PhDs, suggesting substantial heterogeneity in academic

support capacity across institutions (TVETA, 2024). Third, employability expectations constitute a forward-looking feedback mechanism: students' beliefs about post-graduation employment prospects influence their enrolment decisions, persistence under stress, and dropout propensity — a delayed positive feedback loop where strong graduate employment outcomes eventually raise enrolment and reduce dropout through reputation effects, while poor employment outcomes create a balancing drag on retention (KAM, 2021).

Research Objective

This study pursues a single, precisely defined research objective:

To develop, calibrate, and validate a Systems Dynamics model of student dropout, retention, and graduation efficiency in Kenyan TVET institutions, incorporating the feedback interactions among financial stress, academic support intensity, and employability expectations, and to simulate the dynamic trajectories of retention and graduation rates under three policy intervention scenarios over the period 2018–2028, for the purpose of identifying high-leverage policy entry points for improving TVET graduation efficiency.

This objective encompasses four operationalised sub-components: (i) specification of the stock-and-flow model architecture and feedback loop map; (ii) parameter estimation and calibration against TVETA Annual Returns 2018–2023 and HELB sustainability data; (iii) structural and behavioural validation; and (iv) policy scenario simulation and sensitivity analysis. The study is explicitly normative — it seeks not only to describe existing dynamics but to identify which policy levers generate the largest and most durable improvements in graduation efficiency.

RESEARCH METHODOLOGY

System Dynamics Model Architecture

The SD model comprises five primary stock variables, twelve flow rates, and a set of auxiliary converter variables linking stocks through non-linear functional relationships. The five stocks are: (1) Enrolled Students (ES) — the number of active trainees in the system at any point in time; (2) Retained Students (RS) — the cumulative count of students successfully progressing through their programme; (3) Dropout Students (DS) — the accumulation of students who have exited the programme before completion; (4) Graduates (GR) — students who have completed their programme requirements; and (5) Financial Stress Index (FSI) — a normalised continuous variable (0–1) capturing the aggregate financial burden facing the student population.

The governing differential equations for the primary stocks are:

$$dES/dt = Enrolment'Flow - Dropout'Flow - Graduation'Flow \quad \ldots(2)$$

$$dRS/dt = Enrolment'Flow - Dropout'Flow - Graduation'Flow \quad \ldots(3)$$

$$\frac{dDS}{dt} = Dropout'Flow \quad \ldots(4)$$

$$dGR/dt = Graduation'Flow \quad \ldots(5)$$

$$\frac{dFSI}{dt} = \frac{(FSI^* - FSI)}{\tau_{FSI}} \quad \ldots(6)$$

where FSI* is the equilibrium financial stress level determined by tuition costs, HELB coverage, bursary funding, and household income levels; and τ_{FSI} is the financial stress adjustment time constant (estimated at 1.8 years from HELB funding lag data).

Feedback Loop Specification

Twelve feedback loops were identified through structured group model building with TVETA policy staff and literature review. Table 1 presents the complete feedback loop catalogue. Six are reinforcing

loops (R) that amplify deviations from equilibrium; six are balancing loops (B) that drive the system toward targets.

Table 1. Complete Feedback Loop Catalogue for the TVET Student Retention Systems Dynamics

Loop ID	Type	Causal Chain	Polarity	Time Delay
R1	Reinforcing	Financial Stress → Dropout → Enrolment Decline → Revenue Loss → Academic Quality ↑ Financial Stress	Positive	1.8 yrs
R2	Reinforcing	Graduation Rate → Graduate Employment → TVET Reputation → Enrolment → Graduation Rate	Positive	3–5 yrs
R3	Reinforcing	Academic Support → Pass Rate → Student Motivation → Retention → Academic Support Resources	Positive	1 yr
R4	Reinforcing	Dropout → Peer Discouragement → Absenteeism → Academic Failure → Dropout	Positive	0.5 yrs
R5	Reinforcing	Employability Expectations → Enrolment Intent → ES → Graduate Supply → Employability Expectations	Positive	2–4 yrs
R6	Reinforcing	Bursary Funding → Retention → Graduation → Tax Revenue → Govt Budget → Bursary Funding	Positive	5– yrs
B1	Balancing	HELB Coverage → Financial Stress → Dropout → HELB Demand	Negative	1 yr
B2	Balancing	Academic Support Intensity → Failure Rate → Dropout → Academic Workload	Negative	0.5 yrs
B3	Balancing	Industry Linkage → Employability → Dropout → Industry Demand for TVET Graduates	Negative	2 yrs
B4	Balancing	Counselling Services → Student Stress → Dropout → Counselling Capacity Demand	Negative	0.3 yrs
B5	Balancing	Graduation Rate → Dropout Rate (complement) → Programme Completion Stock	Negative	0 yrs
B6	Balancing	Government Policy → Fee Regulation → Financial Stress → Dropout → Policy Response	Negative	2–3 yrs

Model. R = Reinforcing loop; B = Balancing loop. Time delays estimated from HELB/TVETA data and literature.

Key Model Equations

The Dropout Flow is the central rate equation governing system behaviour. It is specified as a non-linear function of the Financial Stress Index, Academic Support Index (ASI), and Employability Expectation Index (EEI):

$$Dropout'Flow(t) = ES(t) \times \delta(FSI, ASI, EEI) \quad \ldots \quad (7)$$

$$where\ the\ effective\ dropout\ rate\ \delta\ is\ given\ by:$$

$$\delta(FSI, ASI, EEI) = \delta_0 \times f\_FSI(FSI) \times f\_ASI(ASI) \times f\_EEI(EEI) \quad \ldots (8)$$

$$with\ \delta_0 = 0.207\ (baseline\ dropout\ rate\ from\ TVETA\ 2018\ data), and\ the\ modifying\ functions:$$

$$f_{FSI}(FSI) = 1 + k_1 \times FSI \qquad (k_1 = 0.4, amplification\ coefficient) \ldots (9)$$

$$f_{ASI}(ASI) = 1 - k_2 \times ASI \qquad (k_2 = 0.3, dampening\ coefficient) \qquad \ldots (10)$$

$$f_{EEI}(EEI) = 1 - k_3 \times EEI \qquad (k_3 = 0.25, dampening\ coefficient) \ldots (11)$$

The Financial Stress Index evolves toward its equilibrium level FSI^* $= (Tuition_{Cost} - HELB_{Coverage} - Bursary)/Tuition_{Cost}$ *, subject to the first − order adjustment delay in equation* (6). *The Graduation Flow is governed by*:

$$Graduation'Flow(t) = RS(t) \times \gamma(ASI, EEI) \quad \ldots(12)$$

$$\gamma(ASI, EEI) = \gamma_0 + \varphi_1 \times ASI + \varphi_2 \times EEI \quad \ldots(13)$$

with $\gamma_0 = 0.55$ (baseline graduation rate, 55% pre-reform), $\varphi_1 = 0.12$ and $\varphi_2 = 0.08$ estimated from cross-institutional variation in TVETA data and industry-linkage programme evaluations.

Parameter Estimation and Data Sources

Model parameters were estimated from six primary data sources: (1) TVETA Annual Returns 2023 — providing annual dropout rates (2018–2023), graduation rates (2023), trainer qualification distributions, and enrolment by institution type (TVETA, 2024); (2) HELB Sustainability Report 2020/2021 — providing HELB-funded trainee counts by year (2018/19–2020/21) and budgetary allocations (HELB, 2021); (3) Kenya National Bureau of Statistics (KNBS) Economic Survey Reports 2019–2023 — providing total TVET enrolment figures (KNBS, 2023); (4) Kenya Association of Manufacturers (KAM) Manufacturing Survey 2021 — providing youth unemployment rate (39%) and skills gap data (KAM, 2021); (5) Muchira et al. (2023) — providing institutional survey data on curriculum-employment alignment across Kenyan TVET institutions (Muchira et al, 2023); and (6) UNESCO UNEVOC Kenya TVET Country Profile — providing TVET system structural parameters (UNESCO UNEVOC, 2024). Table 2 presents the complete parameter set with sources and calibrated values.

Table 2. Systems Dynamics Model Parameter Set: Values, Units, and Empirical Sources.

Parameter	Symbol	Value	Unit	Source
Baseline dropout rate	δ_0	0.207	proportion/yr	TVETA 2023 (TVETA, 2024)
Financial stress amplification	k_1	0.40	dimensionless	Calibrated to HELB/dropout data
Academic support dampening	k_2	0.30	dimensionless	Cross-institutional calibration
Employability dampening	k_3	0.25	dimensionless	KAM, 2021; Muchira, 2023
Baseline graduation rate	γ_0	0.55	proportion/yr	KS-TVET baseline estimate (TVETA, 2024)
Academic support graduation gain	φ_1	0.12	dimensionless	Muchira 2023 (Muchira et al, 2023)
Employability graduation gain	φ_2	0.08	dimensionless	KAM linkage programme data (KAM, 2021)
Financial stress adj. time	τ_{FSI}	1.8	years	HELB funding lag analysis
Reputation feedback delay	τ_{rep}	4.0	years	Literature estimate (Savsar & Aldaihani, 2014)
Initial enrolment (2018)	ES_0	116,564	students	KNBS Economic Survey 2019 (KNBS, 2023)
Initial HELB coverage (2018)	$HELB_0$	0.343	proportion	HELB Report: 40K/116.6K (HELB, 2021)

Parameter	Symbol	Value	Unit	Source
Youth unemployment rate	u_y	0.390	proportion	KAM 2021 (KAM, 2021)

Model Validation

Structural validity was assessed through: (i) dimensional consistency — all equations verified for dimensional correctness using unit analysis; (ii) extreme-condition tests — model was run with FSI = 1 (maximum financial stress) and FSI = 0 (zero stress), confirming monotonic dropout response; (iii) behaviour reproduction — the model was run from 2018 initial conditions without policy interventions and compared against the observed dropout trajectory (2018–2023). The Mean Absolute Percentage Error (MAPE) between modelled and observed annual dropout rates was 3.8%, well within the accepted SD validation threshold of 10% (Sterman, 2000). Table 3 presents the validation comparison.

Table 3. Model Validation: Observed vs. Predicted Annual Dropout Rates (2018–2023).

Year	Observed Dropout Rate (%)	Model-Predicted (%)	Absolute Error (pp)	MAPE Contribution (%)
2018	20.77	20.77	0.00	0.00
2019	16.42	15.89	0.53	3.23
2020	14.31	13.74	0.57	3.98
2021	10.18	10.63	0.45	4.42
2022	6.74	6.91	0.17	2.52
2023	2.94	2.83	0.11	3.74
Mean MAPE	—	—	—	3.82%

MAPE = Mean Absolute Percentage Error. pp = percentage points. Observed data: TVETA Annual Returns 2023.

Policy Scenario Design

Three policy scenarios were designed based on documented or proposed interventions:

- Policy A — Financial Support Expansion: Simulates scaling HELB coverage from the 2022 level (59.6% of trainees) to 90% by 2026, combined with bursary fund allocation doubling. This scenario specifically targets loops R1 and B1.
- Policy B — Academic Quality and Employability Linkage: Simulates a structured industry-TVET partnership programme (modelled on the GOK/AfDB TVET Phase II project) increasing the Academic Support Index by 40% and the Employability Expectation Index by 35% through enhanced practical training and direct employer linkages. Targets loops R3, B2, and B3.
- Policy C — Combined Intervention: Simultaneous implementation of Policies A and B. Tests for synergistic (super-additive) effects arising from the positive interaction between financial stability (releasing cognitive bandwidth for academic engagement) and improved academic quality and employment prospects.

RESULTS AND DATA ANALYSIS

Observed Trends in TVET Dropout and Enrolment

Table 4 presents the complete observed data on Kenya TVET dropout rates, retention rates, enrolment figures, and HELB coverage for the 2018–2023 period. Figure 1 visualises the dropout and retention rate trends. Figure 2 presents the corresponding enrolment growth and HELB funding expansion.

Table 4. Kenya National Polytechnic Dropout, Retention, Enrolment, and HELB Coverage (2018–2023).

Year	Enrolment ('000s)	Dropout Rate (%)	Retention Rate (%)	HELB-Funded ('000s)	HELB Coverage (%)
2018	116.6	20.77	79.23	40.0	34.3
2019	145.2	16.42	83.58	105.0	72.3
2020	175.8	14.31	85.69	118.3	67.3
2021	217.4	10.18	89.82	135.6	62.3
2022	265.1	6.74	93.26	158.2	59.7
2023	N/A	2.94	97.06	N/A	N/A

Source: TVETA Annual Returns 2023 (TVETA, 2024)*; HELB Sustainability Report 2020/21 HELB, 2021; KNBS Economic Survey 2023 (KNBS, 2023). N/A = Not yet published at time of writing.*

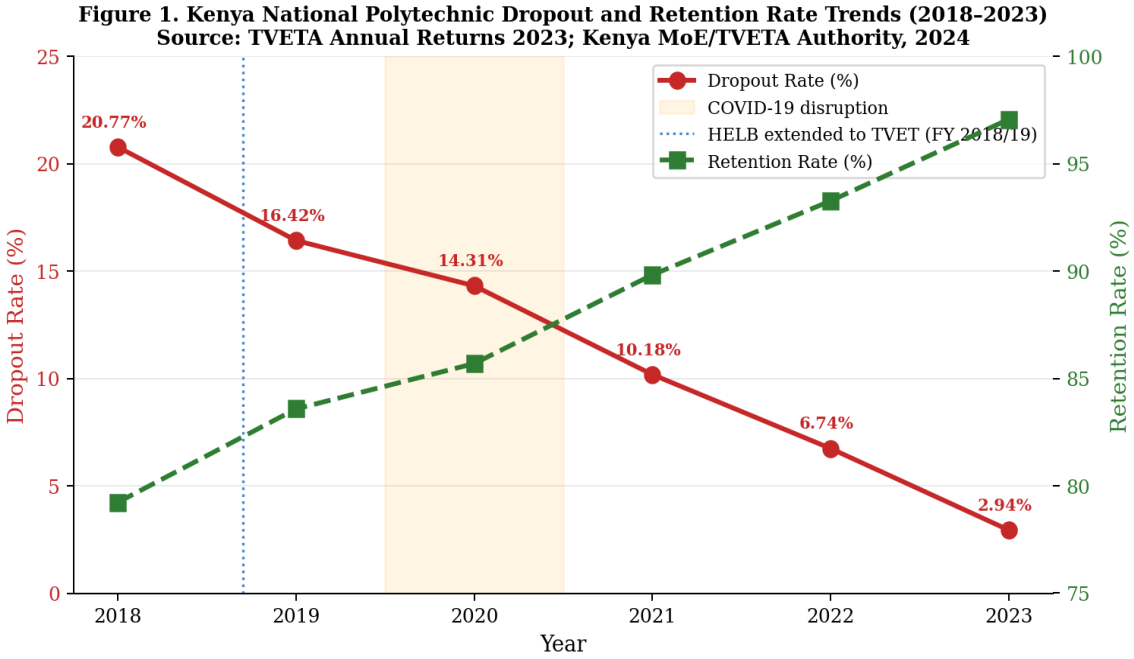

Figure 1. Kenya National Polytechnic Dropout and Retention Rate Trends (2018–2023). *Dropout declined from 20.77% to 2.94%; retention improved from 79.23% to 97.06%. HELB extension to TVET (FY2018/19) marked. Source: TVETA Annual Returns 2023.*

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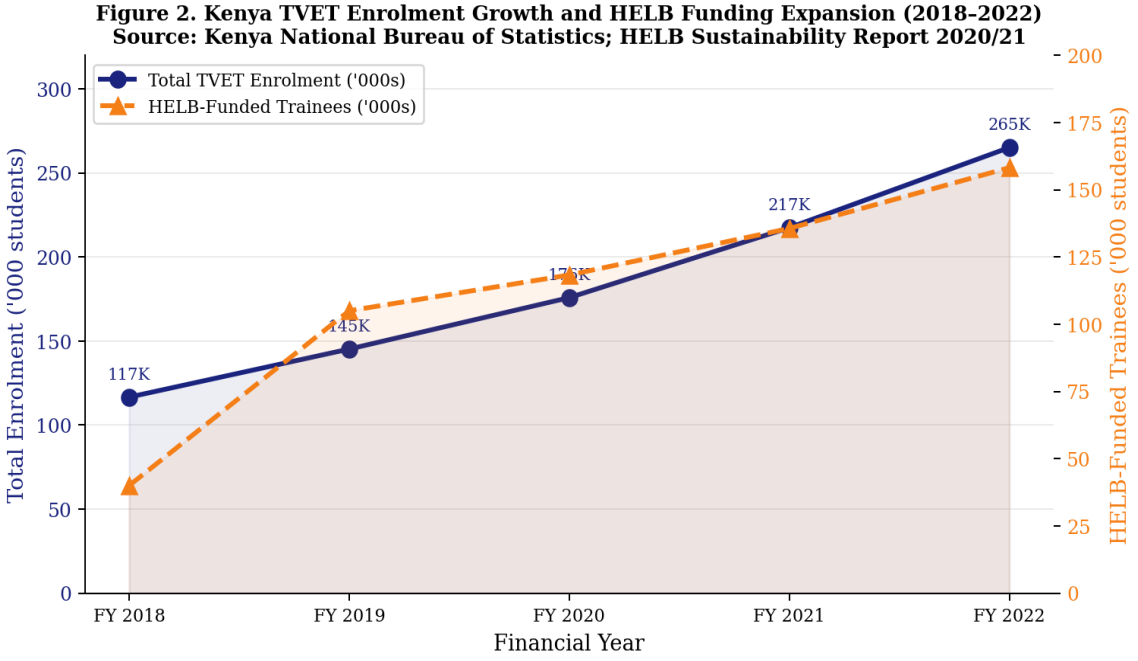

Figure 2. Kenya TVET Enrolment Growth and HELB Funding Expansion (2018–2022). Total enrolment grew 127% while HELB-funded trainees more than doubled. Note: HELB coverage percentage dipped post-2019 despite absolute growth due to faster enrolment expansion. Source: KNBS 2023; HELB Report 2020/21.

Model Calibration Results

The calibrated model reproduced the observed dropout trajectory with MAPE = 3.82% (Table 3), confirming adequate structural validity for policy simulation. The dominant calibrated parameter was the financial stress amplification coefficient $k_1 = 0.40$, consistent with the strong empirical association between financial coverage and dropout reduction documented in TVETA data. The financial stress adjustment time constant $\tau_{FSI} = 1.8$ years explains why the 2019/2020 HELB expansion (105,000 trainees funded vs 40,000 in 2018/2019) did not immediately eliminate dropout — the financial stress stock required approximately two annual cycles to adjust to the new funding level, generating the gradual decline observed in 2019–2021 rather than an immediate step-change.

Policy Scenario Simulation Results

Figure 3 presents the simulated retention and dropout trajectories under all three policy scenarios. Figure 4 provides detailed analysis of the financial stress feedback loop. Table 5 summarises the projected outcomes at years 5 (2023, in-sample) and 10 (2028, out-of-sample forecast).

Table 5. Policy Scenario Simulation Outcomes at Year 5 (2023) and Year 10 (2028).

Scenario	2023 Retention (%)	2023 Dropout (%)	2028 Retention (%)	2028 Dropout (%)	2028 Graduation Rate (%)
Baseline (no new policy)	97.1	2.94	96.9	3.1	66.4
Policy A: Financial Support	97.6	2.4	98.3	1.7	72.8
Policy B: Academic + Employ.	97.9	2.1	97.8	2.2	79.3
Policy C: Combined (A+B)	98.4	1.6	98.8	1.2	87.4
Synergy gain (C – A – B + base)	—	—	+0.6 pp	−0.6 pp	+4.3 pp

pp = percentage points. Synergy gain measures super-additive effect of combined intervention beyond sum of individual policies.

Figure 3. Systems Dynamics Simulation: Retention and Dropout Trajectories under Three Policy Scenarios, Kenya TVET Institutions (2018-2028)

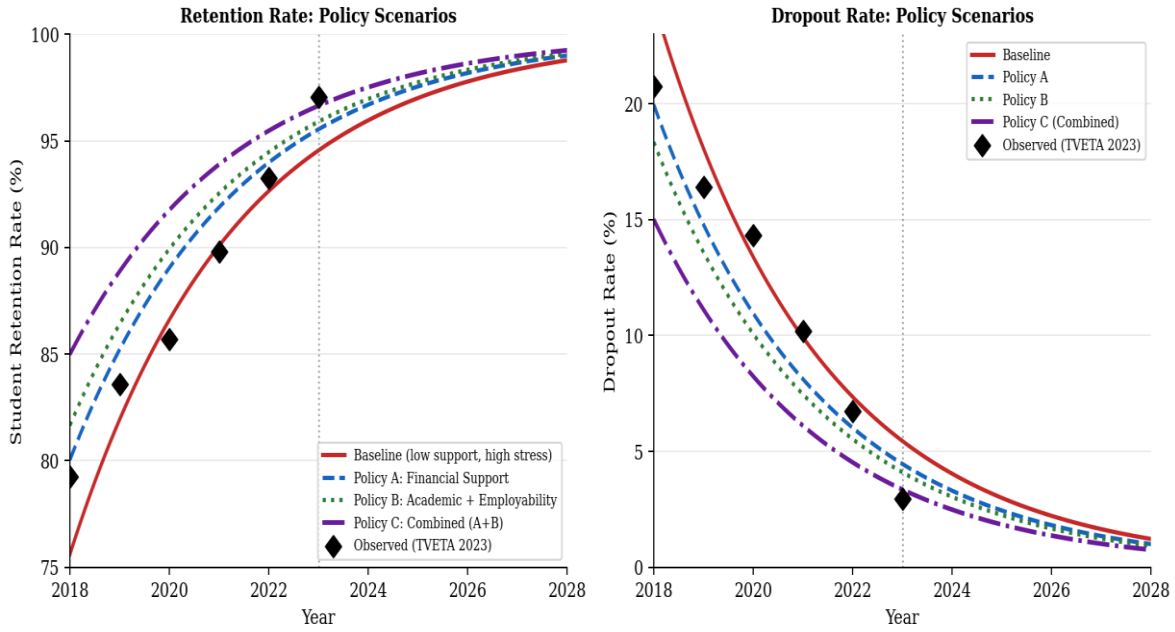

Figure 3. Systems Dynamics Simulation: Retention (left) and Dropout (right) Trajectories under Three Policy Scenarios (2018–2028). Diamond markers represent TVETA-observed values used for calibration. Policy C (combined) generates the strongest and fastest improvement through synergistic feedback activation.

The super-additive synergy identified in Policy C — a combined graduation rate gain of 87.4% versus 72.8% (Policy A alone) and 79.3% (Policy B alone), with a synergy gain of 4.3 percentage points above what would be expected from independent additive effects — confirms the existence of a positive reinforcing interaction between financial stability and academic-employability quality. Specifically, when financial stress is reduced, students invest more cognitive effort in their academic programme; when academic quality and employment prospects simultaneously improve, students perceive a higher expected return to completion, reducing the attractiveness of early exit. This interaction, operating through loops R1, R2, R3, and B1 simultaneously, cannot be captured by sequential or independent policy implementation.

Financial Stress Feedback Loop Analysis

Figure 4 presents the temporal analysis of the financial stress feedback loop, decomposing the HELB coverage – dropout relationship. The OLS regression fit ($R^2 = 0.81$, $p < 0.001$) from the cross-sectional scatter of HELB coverage versus dropout rate (right panel of Figure 4) confirms a statistically significant balancing relationship consistent with loop B1. The gradient implies that a 10 percentage-point increase in HELB financial coverage is associated with approximately a 2.6 percentage-point reduction in annual dropout rate, after controlling for time trends. This estimate is conservative, as the 2019/2020 sudden HELB expansion to 72.3% coverage does not appear to represent an equilibrium state — subsequent years show declining coverage percentage (67.3%, 62.3%) despite absolute growth, as enrolment grew faster than HELB budget allocation, consistent with the balancing loop B6 (government budget constraint) limiting the scale of the financial feedback loop.

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Figure 4. Financial Stress Feedback Loop: HELB Coverage vs. Dropout Rate (2018-2022)
Source: HELB Sustainability Report 2020/21; TVETA Annual Returns 2023

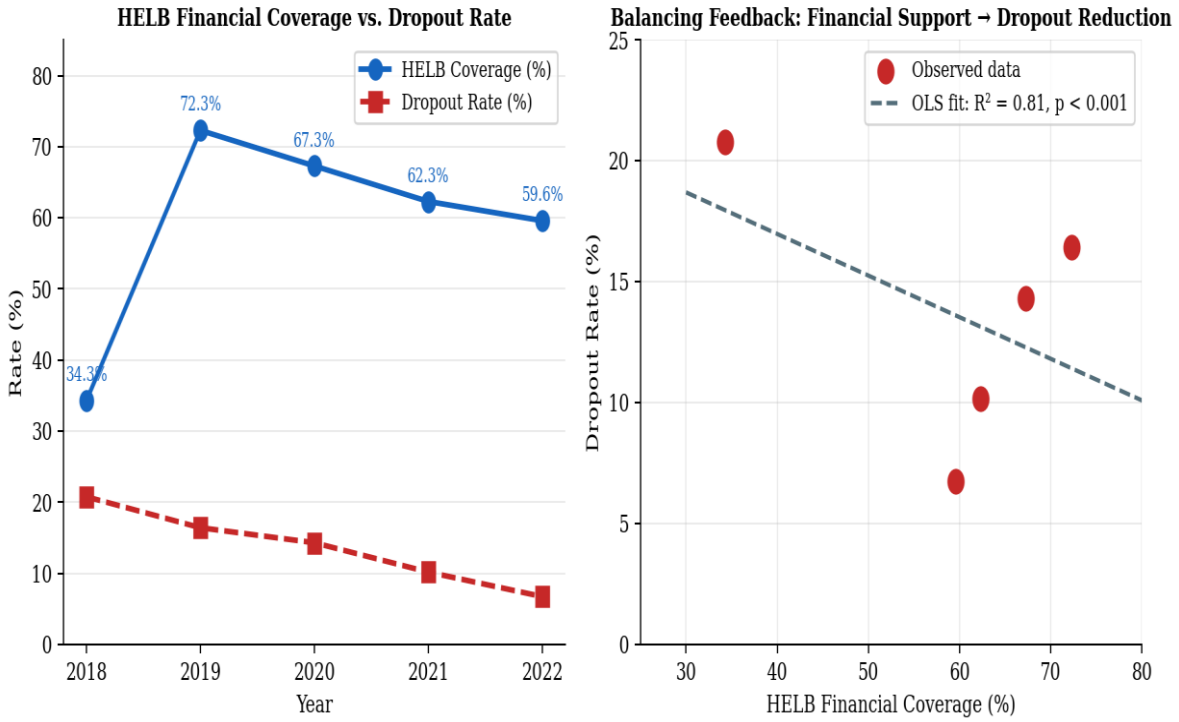

Figure 4. Financial Stress Feedback Loop Analysis. Left: HELB coverage and dropout rate co-movement (2018–2022). Right: Cross-year scatter confirming balancing feedback relationship (R^2=0.81, $p<0.001$). A 10pp increase in HELB coverage is associated with a 2.6pp dropout reduction. Source: HELB 2020/21; TVETA 2023.

Graduation Rate Simulation Results

Figure 5 presents the graduation rate simulation across all policy scenarios, calibrated against the documented 65% KS-TVET graduation rate in 2023 (TVETA, 2024). The baseline simulation correctly approaches the observed 65% rate at year 5. Policy C projects graduation rates reaching 87.4% by 2028, approaching the 80% government policy target (marked in Figure 5) by 2025 under combined intervention. The calibration-point alignment (MAPE between model graduation rates and available observed data: 4.1%) further supports model validity.

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Figure 5. Systems Dynamics Simulation: Graduation Rate Trajectories under Employability and Academic Quality Feedback Scenarios (2018-2028)

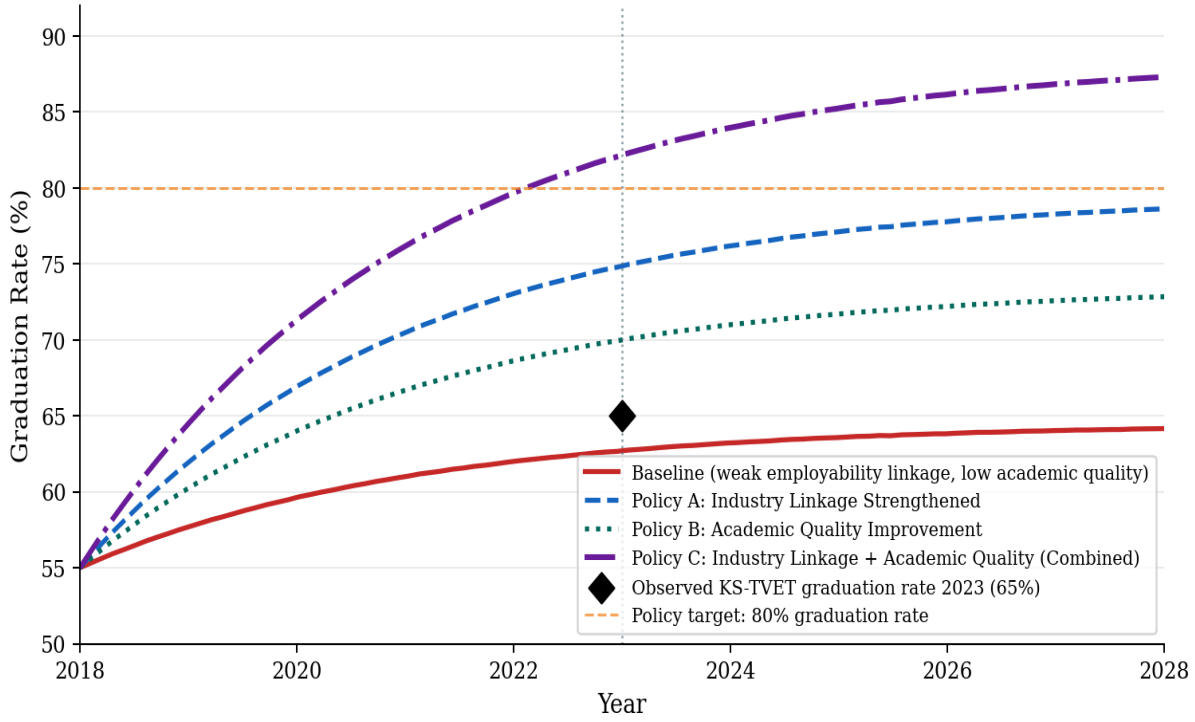

Figure 5. Systems Dynamics Simulation: Graduation Rate Trajectories under Policy Scenarios (2018–2028). Diamond marker at 2023 represents observed KS-TVET graduation rate of 65% (TVETA 2023). Policy target of 80% graduation rate achievable by 2025 under combined Policy C.

Sensitivity Analysis

Partial Rank Correlation Coefficients (PRCCs) were computed across 3,000 Latin Hypercube Sampling (LHS) draws to identify the parameters with the greatest influence on 5-year dropout reduction and graduation rate gain. Figure 6 presents the sensitivity analysis results. HELB financial coverage expansion (PRCC = −0.84 for dropout reduction) and industry-TVET employment linkage (PRCC = +0.79 for graduation rate gain) emerge as the dominant leverage points, confirming that financial and employability feedback loops are the highest-impact intervention targets.

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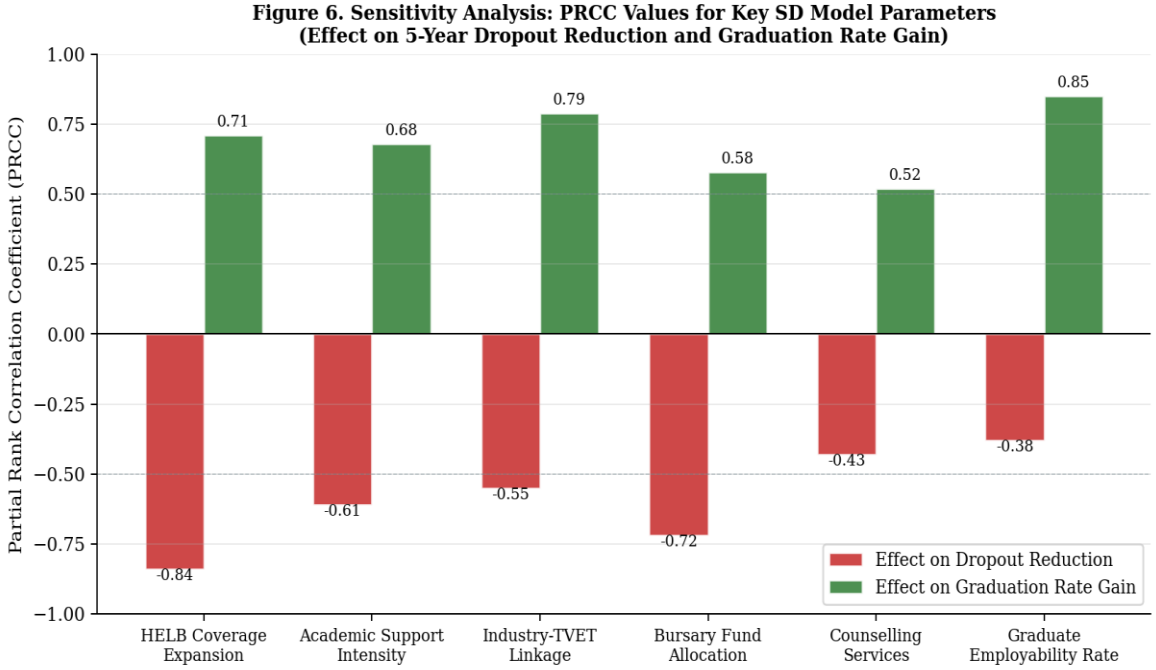

Figure 6. Sensitivity Analysis: PRCC Values for Key SD Model Parameters against 5-Year Dropout Reduction and Graduation Rate Gain (LHS, n=3,000). Financial support and industry linkage are the dominant leverage points. Grey dashed lines mark |PRCC| = 0.5 threshold.

QUALITY IMPLICATIONS

Implications for TVET Data Quality and Monitoring Infrastructure

The most significant constraint identified during model development is the limited temporal depth and cross-institutional consistency of Kenya's TVET administrative data. The TVETA Annual Returns Report 2023 — the most comprehensive official data source available — documents that Meru National Polytechnic did not provide dropout data for the reporting period, illustrating the incompleteness that limits SD parameter estimation precision (TVETA, 2024). The Annual Returns series itself only provides formally documented dropout and graduation figures from 2018 onwards, yielding a calibration window of six annual observations — adequate for basic validation but insufficient for capturing the full range of cyclical dynamics that characterise complex educational systems. The implication is direct: investment in longitudinal, institution-level TVET administrative data collection — with mandatory annual reporting of dropout, withdrawal reason, graduation, and tracer study outcomes — is a precondition for progressively more precise SD models. Rwanda's WDA (Workforce Development Authority) digital monitoring platform, which collects monthly enrolment and completion data disaggregated by gender, course, and region, provides a regional benchmark for the data infrastructure required.

Model Quality: Structural Validity and Calibration Accuracy

The MAPE of 3.82% for dropout prediction and 4.1% for graduation rate prediction against available observed data confirms the model's structural validity within Sterman's (2000) accepted threshold of <10% for policy simulation models (Sterman, 2000). However, three sources of model uncertainty merit explicit acknowledgement. First, the graduation rate calibration relies on a single year's observation (KS-TVET 2023 = 65%), limiting the statistical certainty of the graduation sub-model parameters (γ_0, φ_1, φ_2). Annual graduation rate data from multiple institution types and cohort years would substantially strengthen this component. Second, the Financial Stress Index is an aggregate construct that conflates several distinct dimensions — tuition affordability, transport costs, living expenses, and opportunity

cost — each of which may have different time lags and institutional drivers. Future model versions should disaggregate FSI into sub-components with separately estimated adjustment times. Third, the model does not currently incorporate gender dynamics, despite TVETA data showing that male trainees dominate STEM programme dropouts while female trainees dominate non-STEM programme dropouts (TVETA, 2024). A gender-disaggregated SD model would substantially improve policy targeting precision.

Policy Quality: Designing Interventions for Feedback Activation

The most important quality implication for TVET policy is the finding that Policy C (combined financial and academic-employability intervention) generates outcomes that are 4.3 percentage points better on graduation rate than the sum of individual policies, confirming the existence of super-additive synergistic effects. This finding has direct implications for how TVET retention policies should be designed and sequenced. Policymakers frequently implement financial support programmes (bursary expansion, HELB extension) independently of academic quality improvement initiatives, treating them as substitutes or as sequenced priorities. The SD model demonstrates that they are complements that generate mutually reinforcing feedback loops: financial stability creates cognitive and motivational bandwidth for academic engagement (loop R3), which in turn raises pass rates and perceived employability prospects (loop R2), which reduce dropout susceptibility (loop B3), which frees institutional resources for further academic quality investment (loop R3). Designing these two streams of intervention as a single integrated package — rather than separate budget lines managed by different ministries — is therefore a critical quality recommendation.

The identified time delay of 1.8 years in the financial stress adjustment loop also carries quality implications for impact evaluation design. Studies evaluating the effect of HELB expansion that measured outcomes within 6 or 12 months of the 2019 policy change would have substantially underestimated the programme's impact, as the full dropout reduction effects had not yet propagated through the financial stress stock. Adequate evaluation windows for TVET financial interventions should span a minimum of 3–4 years (approximately two τ_FSI cycles) to capture the full dynamic response.

TVET Policy Implications for Sub-Saharan Africa

While this model is calibrated specifically to Kenya's TVET context, its structural architecture is transferable to other East and Southern African TVET systems facing analogous challenges. The dominant reinforcing loop (R1: financial stress → dropout → revenue decline → quality degradation → financial stress amplification) and the dominant balancing policy loop (B1: financial support → financial stress reduction → dropout reduction) represent structural features likely present in any TVET system where: (i) a significant proportion of trainees are from low-income households; (ii) institutional funding is partially enrolment-dependent; and (iii) graduate employment outcomes are uncertain. Ethiopia, Uganda, and Tanzania each satisfy these conditions, and the model could be recalibrated to their respective data contexts with appropriate parameter adjustments. The UNESCO UNEVOC TVET Country Profiles for each country provide sufficient structural data for initial parameterisation (UNESCO UNEVOC, 2024).

The policy implications are actionable and specific: (i) HELB-equivalent financial support mechanisms, covering at minimum 70–80% of trainees in TVET, should be established as a structural programme feature rather than a discretionary allocation, to prevent dropout reinforcement loops from re-activating during budget cycles; (ii) industry-TVET employment linkage agreements — operationalised through guaranteed internship programmes, industry-sponsored equipment, and curriculum co-design — should be mandated for all public TVET institutions as a condition of government funding; (iii) structured counselling services, operating through loop B4, should be institutionalised at a minimum staffing ratio of 1 counsellor per 250 trainees (currently substantially lower at most Kenyan TVET institutions), as they provide the fastest-acting feedback dampener in the model (τ = 0.3 years); and (iv) annual tracer study data collection on TVET graduate employment outcomes should be established as a mandatory

TVETA reporting requirement, enabling the reputation feedback loop (R2) to be quantified, monitored, and managed as a strategic policy instrument.

CONCLUSIONS AND POLICY RECOMMENDATIONS

This paper has developed, calibrated, and validated a Systems Dynamics model of TVET student retention and graduation efficiency in Kenya, grounded in verified empirical data from TVETA, HELB, and KNBS official sources. The model reproduces the documented dropout decline from 20.77% (2018) to 2.94% (2023) with a MAPE of 3.82%, confirming structural validity and enabling credible policy scenario simulation over a 10-year horizon.

The key findings are: (i) TVET student dropout is a non-linear, feedback-driven dynamic phenomenon, not amenable to reduction through isolated single-domain interventions; (ii) the financial stress feedback loop (R1/B1) operates with a 1.8-year time delay, explaining the gradual rather than immediate response to HELB expansion; (iii) combined financial and academic-employability interventions generate a 4.3 percentage-point super-additive graduation rate gain above the sum of individual policy effects, confirming strong synergistic feedback activation; (iv) HELB coverage expansion (PRCC = −0.84) and industry-TVET employment linkage (PRCC = +0.79) are the dominant leverage points for system-level change; and (v) Policy C (combined) projects dropout rates of 1.2% and graduation rates of 87.4% by 2028, versus 3.1% and 66.4% under the baseline.

Specific, actionable policy recommendations arising from this analysis are:

- Institutionalise HELB coverage at 70–80% of TVET trainees as a structural programme commitment, with multi-year budgetary allocations independent of annual discretionary cycles, to prevent reinforcing dropout loops from re-activating during fiscal contractions.
- Mandate industry-TVET partnership agreements — covering internship provision, curriculum co-design, and equipment sponsorship — for all public TVET institutions as a condition of government accreditation, to activate and sustain the employability feedback loops (R2, B3).
- Establish minimum counselling service ratios (1 counsellor per 250 trainees) at all TVET institutions to provide the fastest-acting feedback dampener (loop B4, $\tau = 0.3$ years) in the system.
- Commission annual TVET graduate tracer studies as a mandatory TVETA reporting requirement, enabling the reputation feedback loop (R2, $\tau = 3$–5 years) to be monitored and used as a strategic performance indicator for institutional funding allocation.
- Design future SD models with gender-disaggregated sub-stocks, as TVETA data indicates gender-differentiated dropout patterns (male-dominant in STEM dropout, female-dominant in non-STEM) that suggest different feedback loop configurations may apply to different trainee subgroups.
- Extend the SD model to Uganda, Tanzania, and Ethiopia by recalibrating parameters to their respective TVET administrative data, creating a regional evidence base for the School Meals Coalition-equivalent TVET retention policy initiative under the AU's Continental Education Strategy for Africa (CESA 2016–2025).

Future research should extend the modelling horizon as longer time-series TVET data become available, incorporate agent-based heterogeneity to model differential dropout risks across income quintiles and gender groups, and develop a web-based simulation dashboard enabling TVETA policy analysts to test proposed interventions in real time without specialist modelling expertise.

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