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Infrastructure, Education Spending, and Economic Growth: Absorptive Capacity Constraints on Complementarity across Sub-Saharan Africa, Asia, and Latin America

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Research Article

Keywords: Infrastructure Investment, Education Spending, Economic Growth, Absorptive Capacity, Public Expenditure Tracking, Sub-Saharan Africa, Pooled Mean Group Estimation

Posted Date: September 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10882941/v1

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Additional Declarations: The authors declare no competing interests.

Abstract

This study tests a working assumption of coordinated development policy: that infrastructure and education spending generate complementary growth returns. Using a panel of 115 developing economies across Sub-Saharan Africa, Asia, and Latin America (1970–2023), and an augmented Solow-Barro growth framework estimated via Pooled Mean Group (PMG) and Dynamic Fixed Effects (DFE) estimators, the analysis finds that this assumption does not hold. Conditional convergence is strong, and capital formation is the most consistent long-run growth driver. Digital infrastructure — proxied by mobile connectivity — delivers positive, significant effects, particularly in Latin America and Sub-Saharan Africa, while traditional infrastructure and education spending show limited independent effects. Critically, education expenditure does not activate infrastructure's growth returns in any region studied. Where an interaction is detectable — a negative, significant education×mobile-connectivity term in Sub-Saharan Africa — it signals absorptive-capacity failure rather than synergy. For development economics, this reframes a widely used policy prescription: infrastructure–education co-investment programmes deliver growth dividends only where institutional and human-capital preconditions already exist, not from spending coordination alone. Drawing on public expenditure tracking and teacher absenteeism evidence, the paper identifies expenditure leakage and service-delivery failure as concrete channels through which budgeted education spending fails to build growth-relevant human capital.

JEL Classification: O11; O15; O43; H52; C23

1. Introduction

Public investment in infrastructure and education is widely recognised as foundational to long-run growth in developing economies, yet a critical assumption embedded in coordinated investment frameworks has gone largely untested: that education expenditure activates the growth benefits of infrastructure. Classical growth theory establishes that physical and human capital accumulation jointly underpin long-run income growth, while more recent work emphasises that investment outcomes depend critically on institutional quality, macroeconomic stability, and absorptive capacity (Solow, 1956; Barro & Sala-I-Martin, 1992). Despite this, development economics has largely examined infrastructure and education spending in isolation, leaving the interactive growth effects that coordinated-investment policy assumes largely untested empirically.

The assumption that co-investing in both sectors generates complementary returns is influential. It underlies coordinated development strategies across Sub-Saharan Africa, Asia, and Latin America, where infrastructure deficits, education access gaps, and persistent productivity shortfalls remain defining challenges (OECD, 2024). Yet whether education spending actually unlocks the growth potential of infrastructure — or whether the binding constraint lies in institutional and human-capital conditions rather than in spending levels — has not been examined comparatively across these regions, despite its centrality to how multilateral lenders and national planning agencies sequence public investment.

This paper's central finding is that education expenditure does not activate infrastructure complementarity in the long run, and that this holds consistently across Sub-Saharan Africa, Asia, and Latin America. The failure is not a data artefact: it reflects a structural condition in which spending coordination cannot substitute for the absorptive capacity — human capital quality and institutional depth — that would make such coordination effective. Using a dynamic panel framework covering 115 developing countries over 1970–2023, the paper shows that a widely used class of development policy recommendation — that infrastructure and education budgets should be planned and disbursed jointly to compound their growth effects — rests on an assumption the data do not support. The policy implication is a reorientation, not away from coordinated planning as such, but toward sequencing: building the institutional and human-capital conditions under which coordinated investment can generate returns, before scaling the investment itself.

The same institutional logic reappears in a second, independent result: a convergence reversal among institutionally less stable Asian economies, where higher initial income predicts faster rather than slower subsequent growth — the opposite of the standard neoclassical prediction. This is not a separate finding but the same mechanism working through a different channel. Where institutional capacity is absent, neither infrastructure nor education spending delivers its expected growth dividend, and the catch-up dynamics that development economics ordinarily expects of poorer economies break down. Together, the two results speak directly to how developing regions should sequence and condition public investment, and to why spending-based coordination frameworks are insufficient on their own — a conclusion with direct bearing on how the World Bank, regional development banks, and national planning agencies design multi-sector investment programmes. Section 2.7 draws on public expenditure tracking and service-delivery evidence to identify concrete channels — administrative leakage and teacher absenteeism — through which this constraint is most likely to operate.

2. Literature Review

2.1 Economic Growth, Infrastructure, and Human Capital

The foundational literature in growth economics identifies physical and human capital as core drivers of long-run economic performance. Solow's 1956 seminal model emphasised capital accumulation and exogenous technological progress as engines of growth, while Barro and Sala-I-Martin, (1992,2004) extended this framework to introduce human capital and conditional convergence into cross-country growth analysis. These models suggest that economies converge towards their steady states as capital deepens and technology diffuses, but crucially indicate that the *quality* and *composition* of capital matter for growth outcomes.

Empirically, infrastructure has been associated with higher productivity by lowering transport costs, increasing market access, and strengthening connectivity (Calderón & Servén, 2004; Canning & Pedroni, 2004). Infrastructure gaps are shown to disproportionately constrain growth in low-income environments, where poor road networks, unreliable power supply, and limited digital access raise transaction costs and impede structural transformation (Fay & Morrison, 2005; Foster and Briceño-Garmendia, 2010). Human capital, generally proxied by education outcomes, is robustly linked to income growth through improvements in worker skills, technological adoption, and innovation capacity (Hanushek and Woessmann, 2008; Barro, 2013). Importantly, human capital

also conditions the productivity returns to physical capital, including infrastructure, and enhances the capacity of economies to absorb advanced technologies (Benhabib & Spiegel, 1994).

2.2 Infrastructure and Growth: Regional Experiences

A rich strand of literature examines the growth effects of infrastructure investment across different regions. In Asia, high levels of public investment in transport, energy, and communications have been credited with facilitating industrialisation and export competitiveness, especially in East and Southeast Asia (Aschauer, 1989; Calderon & Serven, 2010). Recent World Bank and ADB reports highlight that infrastructure expansion has been central to Asia's rapid growth and poverty reduction, though returns vary with governance quality and investment efficiency.

In contrast, Latin American economies have historically struggled with infrastructure deficits and underinvestment compared to OECD benchmarks, limiting regional integration and competitiveness (IDB, 2017). Studies using panel data report that infrastructure quality is positively associated with productivity in Latin America, but gains are muted by bottlenecks in urban logistics and volatile investment cycles (Suárez-alemán et al., 2019; (Pagliuca, Álvarez, Santos, Serebrisky and Suárez-Alemán, 2022).

Sub-Saharan Africa exhibits some of the largest global infrastructure gaps, with over half the population lacking access to electricity in many countries and road networks insufficient to connect rural producers to markets (Foster, Vivien;Briceño-Garmendia, 2010; OECD, 2025) Cross-country analyses confirm that infrastructure shortfalls significantly reduce potential growth and private investment, although estimates vary depending on methodological choices and data periods (Calderon & Serven, 2010; Foster et al., 2025).

2.3 Education Spending and Growth Dynamics

Education spending and human capital formation are critical for improving labour productivity and facilitating economic structural change. Macro-level studies find robust positive associations between education expenditure and per-capita GDP growth, particularly when quality indicators (e.g., test scores, completion rates) are incorporated ((Hanushek and Kimko, 2000); Barro & Lee, 2012). Cross-regional evidence suggests returns to education are highest where returns to skills are integrated with labour market demand, underscoring the importance of policies that link schooling with productive employment ((Montenegro and Patrinos, 2014); UNESCO, 2024).

In Latin America, education spending has increased over recent decades, yet learning outcomes remain below international averages, which partly explains weaker growth impacts from schooling investments (ECLAC, 2024; UNESCO, 2024). In Sub-Saharan Africa, challenges in education quality, teacher shortages, and inadequate facilities dampen the growth benefits of schooling despite rising enrolment rates (UIS, 2024). Asia's experience indicates more consistent improvements in both access and quality, particularly in East Asia, where strong education systems have supported technological upgrading and productivity gains (Hanushek & Woessmann, 2008).

2.4 Complementarity between Infrastructure and Human Capital

Recent empirical work emphasises that infrastructure and education may **complement each other** in raising productivity and fostering growth. Theoretically, infrastructure enhances access to schools and markets, while education improves the capacity of the workforce to exploit new technologies and infrastructure services. Some panel studies find that the combined effects of infrastructure and human capital are greater than their separate contributions, particularly in middle-income and emerging economies (Foster et al., 2025; Calderón et al., 2011). However, evidence remains mixed, in part due to challenges in measuring complementarities and the limited use of methodologies that allow for regional heterogeneity in long-run relationships. A critical but often underemphasised dimension of this complementarity question is absorptive capacity — the extent to which an economy possesses the human capital quality and institutional conditions necessary to translate infrastructure investment into productivity gains. Borensztein et al. (1998) demonstrate in the context of FDI that technology spillovers materialise only above a minimum human capital threshold, implying that spending on education is a necessary but not sufficient condition for infrastructure to generate growth. Azman-Saini et al (2010) extend this logic, showing that the growth-enhancing effect of technology transfers is contingent on the quality rather than quantity of human capital accumulation. Applied to the present study, these findings imply that the relevant question is not whether infrastructure and education spending co-move, but whether education expenditure builds the absorptive capacity needed to make infrastructure productive. Where institutional instability, low education quality, and weak labour market linkages prevail — as in much of Sub-Saharan Africa and less stable Latin American economies — higher spending may not translate into the human capital depth required to activate complementarity. This framing provides the theoretical foundation for interpreting the negative and significant edug×mcs interaction observed in the empirical results.

2.5 Dynamic Adjustment and Long-Run Convergence

Much of the early literature focused on static cross-sectional associations between investment and growth, obscuring dynamic adjustment processes. The growing use of **dynamic panel methods** — including the Pooled Mean Group (PMG) estimator — has enabled researchers to differentiate between *short-run dynamics* and *long-run equilibrium relationships* while allowing for regional heterogeneity (Pesaran et al., 1999; Samargandi et al., 2015). These methods have been applied to analyse FDI-growth links and conditional convergence in distinct regions, revealing that adjustment speeds vary significantly with macroeconomic stability and institutional quality (Eberhardt & Teal, 2011; Alguaci, Cuadros and Orts, 2011). Within the PMG literature, several findings are directly relevant to the present study. Samargandi et al. (2015) apply PMG to a cross-country panel and find that long-run growth relationships are sensitive to the composition of investment — a finding that motivates the inclusion of interaction terms in the present specification. Eberhardt and Teal (2011) caution that imposing long-run slope homogeneity, as PMG does, may mask important cross-country heterogeneity, particularly in developing regions where institutional quality varies substantially — an issue this study addresses through regional and stability-regime sub-samples. Chanegriha et al. (2020) demonstrate that error-correction speeds and FDI-growth linkages differ systematically between more and less institutionally developed economies, providing theoretical support for the stability-regime splits employed in the Asian and Latin American sub-sample analysis. Collectively, this body of work

affirms that the PMG framework, when combined with appropriate sub-sample disaggregation, is well-suited to identifying long-run complementarity effects across heterogeneous developing regions.

2.6 Gaps and the Need for Comparative Evidence

Despite the extensive literature on infrastructure, education, and growth, the development economics literature leaves several gaps unaddressed. First, most studies treat infrastructure and education spending independently, limiting insight into **their joint or interacting effects**. Second, much of the evidence is region-specific, with limited comparative work that simultaneously assesses long-run growth determinants across *Sub-Saharan Africa, Latin America, and Asia*. Third, while recent research acknowledges conditional effects and thresholds (e.g., institutional quality, macroeconomic stability), few studies integrate these conditions within a dynamic error-correction framework that explicitly tests for **complementarity and convergence** across major developing regions. Fourth, while the absorptive capacity literature (Borensztein et al., 1998; Azman-Saini et al 2010) identifies human capital quality as the binding constraint on technology-growth linkages, this mechanism has not been explicitly tested within a dynamic panel error-correction framework applied comparatively across SSA, Asia, and Latin America. This study addresses all four gaps.

2.7 Mechanisms of Absorptive Capacity Failure: Evidence from the Public Finance and Service-Delivery Literature

The absorptive capacity interpretation offered above names a constraint without identifying the channel through which it operates. Two strands of public-finance and service-delivery research point to concrete mechanisms by which budgeted education spending fails to convert into growth-relevant human capital, independent of the amount spent.

The first is expenditure leakage. Public Expenditure Tracking Surveys (PETS) in Uganda found that, prior to a public disclosure reform, schools received on average only 13 percent of the non-wage capitation grant budgeted for them, with the remainder absorbed by intermediate administrative layers before reaching the classroom (Reinikka & Svensson, 2004). Comparable tracking studies in other Sub-Saharan African education systems have documented similarly large gaps between budgeted and delivered resources, driven by weak public financial management and limited expenditure oversight rather than by the level of the education budget itself.

The second is service delivery failure at the point of use. Chaudhury, Hammer, Kremer, Muralidharan, and Rogers (2006) document teacher absence rates averaging 19 percent across a six-country sample of developing economies, with rates exceeding this average in several Sub-Saharan African systems; absent teachers represent budgeted, disbursed spending that nonetheless fails to produce instruction. Both channels imply that the growth-relevant input is not budgeted expenditure (*edug*) but expenditure net of administrative leakage and delivery failure, and that this gap between budgeted and effective spending should widen as public financial management quality and administrative capacity weaken — conditions that vary systematically, and are more severe on average, across the three regions studied here than within any single one of them.

These channels offer a substantive rather than a residual explanation for the study's central empirical pattern: the negative and significant interaction between education spending and mobile connectivity in Sub-Saharan Africa, alongside null rather than positive interaction effects in Asia and Latin America. Rather than treating this heterogeneity as unexplained cross-regional noise, it is consistent with known differences in public expenditure tracking and service-delivery performance documented in the literature above, and with World Bank Public Expenditure and Financial Accountability (PEFA) assessments, which score Sub-Saharan African budget execution and expenditure-control systems below the averages recorded for comparable middle-income Asian and Latin American economies. The interaction terms estimated in Section 4 should accordingly be read as an aggregate, reduced-form signature of these delivery-chain failures rather than as evidence that education spending is, in principle, unproductive.

3. Methodology

3.1 Empirical Framework

To examine the complementary effects of infrastructure and education spending on economic growth across Sub-Saharan Africa, Asia, and Latin America, this study adopts a **dynamic panel data framework** that distinguishes between **short-run adjustment dynamics** and **long-run equilibrium relationships**. This approach is motivated by growth theory, which suggests that investment in physical and human capital influences long-run output levels, while short-run growth paths may differ across countries due to structural rigidities, macroeconomic shocks, and institutional heterogeneity.

Following the augmented Solow growth framework (Mankiw et al., 1992); Barro & Sala-i-martin, 2004), output growth is modelled as a function of initial income, infrastructure development, education spending, and a vector of standard growth control variables. The baseline long-run relationship is specified as:

$$gdpgp_{it} = \alpha_i + \beta_1 \mathrm{Infra}_{it} + \beta_2 \mathrm{Edu}_{it} + \beta_3 (\mathrm{Infra}_{it} \times \mathrm{Edu}_{it}) + \gamma' X_{it} + \epsilon_{it}$$

where $gdpgp_{it}$ denotes real GDP per capita in country i at time t, Infra_{it} represents infrastructure indicators, Edu_{it} captures education spending, and X_{it} is a vector of control variables including gross fixed capital formation, population growth, trade openness, inflation, and government consumption. The interaction term captures **complementarity** between infrastructure and education spending.

3.2 Dynamic Error-Correction Specification

To capture both short-run dynamics and long-run convergence, the model is re-parameterised into an **error-correction form**, consistent with Pesaran, Shin and Smith (1999):

$$\Delta y_{it} = \phi_i \left(y_{i,t-1} - \theta_1 \text{Infra}_{i,t-1} - \theta_2 \text{Edu}_{i,t-1} - \theta_3 (\text{Infra} \times \text{Edu})_{i,t-1} - \theta' X_{i,t-1} \right) + \sum_{k=1}^{p-1} \lambda_{ik} \Delta y_{i,t-k} + \sum_{k=0}^{q-1} \delta_{ik} \Delta Z_{i,t-k} + u_{it}$$

where ϕ_i is the **speed of adjustment coefficient**. A negative and statistically significant ϕ_i provides evidence of **long-run convergence**, indicating that deviations from equilibrium are corrected over time. Allowing ϕ_i to vary across countries accommodates heterogeneity in adjustment speeds arising from differences in institutional quality, macroeconomic stability, and policy environments.

3.3 Estimation Technique

The primary estimator employed is the **Pooled Mean Group (PMG)** estimator developed by Pesaran et al. (1999). PMG constrains long-run coefficients to be homogeneous across countries within each region, while allowing short-run dynamics, intercepts, and adjustment speeds to differ. This choice is appropriate for the present study for three reasons.

First, the regions under study are characterised by **shared long-run growth mechanisms**, but differ substantially in short-run responses to shocks. Second, PMG performs well in panels with relatively long-time dimensions, which is typical of macroeconomic growth data. Third, PMG allows for meaningful interpretation of **regional convergence behaviour**, which is central to the study's objectives.

For robustness, PMG estimates are compared with alternative estimators, specifically the **Dynamic Fixed Effects (DFE)** estimator. Hausman tests are employed to assess the validity of the long-run homogeneity restriction imposed by PMG.

3.4 Data and Variables

The analysis uses a balanced panel of countries from **Sub-Saharan Africa, Asia, and Latin America** over the period 1970–2023. Real GDP per capita (constant prices) is sourced from the World Development Indicators (WDI). Infrastructure is proxied using indicators capturing **transport, energy, and digital connectivity**, such as Logistics Performance Indicators (LPI), mobile cellular subscriptions (mcs), access to electricity(ac). Education spending is measured as **public expenditure on education as a percentage of GDP (edug)**, reflecting government commitment to human capital formation. Two measurement considerations warrant explicit acknowledgement. First, expenditure-based proxies capture fiscal inputs rather than education quality outcomes. Quality-adjusted human capital measures consistently generate stronger and more robust growth associations than expenditure levels alone (Hanushek & Woessmann, 2008), and the null and negative interaction results reported in Section 4 are best understood as reflecting the failure of spending to build effective human capital rather than a genuine null effect of education on growth. Second, the use of edug as the education proxy is motivated by **data availability across the full panel period and by the study's focus on public investment** decisions; coefficient estimates on education and interaction terms should be interpreted as the growth effects of public education spending, not of human capital accumulation per se.

Control variables follow standard growth regressions and include gross fixed capital formation, population growth, terms of trade(tot), broad money(bm), initial income (loglgdpp), and government expenditure (gove). All variables are transformed into logarithms where appropriate to facilitate elasticity interpretation and reduce heteroskedasticity.

Table 1
Variable Definitions, Measurements, and Data Sources

Category	Variable	Code	Definition and measurement	Source	Transformation
Dependent variable	GDP per capita growth	*gdpgp*	Annual growth rate of real GDP per capita (constant 2015 USD)	WDI	First difference of log GDP per capita
Infrastructure	Access to electricity	*ae*	Share of population with access to electricity (%)	WDI	Levels
	Mobile cellular subscriptions	*mcs*	Mobile cellular telephone subscriptions per 100 people	WDI	Levels
	Logistics Performance Index	*LPI*	World Bank composite index of logistics and trade infrastructure quality (1–5 scale); available from 2007	World Bank LPI	Levels
Education spending	Public education expenditure	*edug*	Government expenditure on education as a percentage of GDP	WDI	Levels
Complementarity	Education × Electricity	*edugae*	Multiplicative interaction of edug and ae	Constructed	edug × ae
	Education × LPI	*edugLPI*	Multiplicative interaction of edug and LPI	Constructed	edug × LPI
	Education × Mobile	*edugmcs*	Multiplicative interaction of edug and mcs	Constructed	edug × mcs
Control variables	Gross fixed capital formation	*gfcf*	Gross fixed capital formation as a percentage of GDP; proxy for physical capital accumulation	WDI	Levels
	Government expenditure	*gove*	General government final consumption expenditure as a percentage of GDP	WDI	Levels
	Population growth	*popg*	Annual population growth rate (%)	WDI	Levels
	Initial income	*loglgdpp*	Lagged log of real GDP per capita (constant 2015 USD); proxy for conditional convergence	WDI	Log-transformed; lagged one period
	Terms of trade	*tot*	Net barter terms of trade index (2000 = 100)	WDI	Levels
	Broad money	*bm*	Broad money (M2) as a percentage of GDP; proxy for financial depth	WDI	Levels

Notes: WDI = World Development Indicators (World Bank). All macroeconomic variables are sourced from WDI unless otherwise stated. The Logistics Performance Index (LPI) is published biennially from 2007; earlier-period values are treated as missing. Interaction terms are constructed as multiplicative products of public education expenditure and each infrastructure proxy. Variables are log-transformed where appropriate to facilitate elasticity interpretation and reduce heteroskedasticity. The panel covers Sub-Saharan Africa (n = 47), Asia (n = 38), and Latin America (n = 30) over 1970–2023.

The baseline model is estimated separately for Sub-Saharan Africa, Asia, and Latin America, allowing long-run coefficients and convergence speeds to differ across regions. Robustness is assessed by comparing PMG estimates with Dynamic Fixed Effects (DFE) and by re-estimating the model after excluding broad money and terms of trade. Hausman tests are used to validate the long-run homogeneity restriction. The analysis focuses on three outcomes: the magnitude and significance of long-run infrastructure and education coefficients; the sign and significance of interaction terms as evidence of complementarity; and the speed of adjustment as an indicator of conditional convergence. Endogeneity and robustness of the baseline results are also checked through Instrumental Variable (IV) and GMM regressions to ensure the validity of these results.

4. Results and Discussion

This section presents PMG and DFE long-run estimates across three regions and their stability-regime sub-samples. The central question throughout is not whether infrastructure and education spending affect growth independently — the evidence on physical capital accumulation and digital connectivity is consistent and robust — but whether education expenditure activates complementarity with infrastructure. The results show that it does not, and that where interaction effects appear, they reflect absorptive capacity failure rather than synergy. The Asian less stable sub-sample additionally documents a reversal of the standard convergence dynamic, with results interpreted in light of the absorptive capacity and poverty trap literatures introduced in Section 2.

4.1 Asia

Table 2
Long-Run Estimates from DFE and PMG Models (Asia Sample, 1970–2023)

Variable	DFE		PMG		
	Coef.	**(SE)**	**Coef.**	**(SE)**	**Difference**
ae	-0.0690	(0.0395)	-0.0204	(0.0246)	-0.0486
bm	-0.0070	(0.0093)	-0.0011	(0.0058)	-0.0060
gove	-0.0530	(0.0317)	-0.0309	(0.0193)	-0.0221
gfcf	0.1610***	(0.0327)	0.1309***	(0.0195)	0.0301
popg	-0.2730**	(0.1123)	-0.5056***	(0.1020)	0.2326
loglgdpp	-0.4284	(0.3069)	-0.5621***	(0.1872)	0.1337
tot	-0.0003	(0.0050)	0.0037	(0.0038)	-0.0040
LPI	-2.5908	(1.8457)	-2.6361**	(1.0328)	0.0453
mcs	0.0134	(0.0100)	-0.0078	(0.0076)	0.0212
edug×ae	0.0089	(0.0105)	-0.0014	(0.0068)	0.0103
edug×LPI	-0.2166	(0.3119)	0.0337	(0.2009)	-0.2503
edug×mcs	-0.0037	(0.0021)	0.0009	(0.0018)	-0.0045
Error correction term					
Model	**Coef.**	**(SE)**			
DFE	-0.8021***	(0.0219)			
PMG	-0.7297***	(0.0490)			
Model diagnostics					
Observations	2,014	Groups	38		
Hausman $\chi^2(12)$	1.07	Prob > χ^2	1.0000		
Preferred estimator	PMG				

Notes: *Dependent variable: Δgdpgp (GDP per capita growth). Standard errors in parentheses. *** p < 0.01; ** p < 0.05. Difference = DFE coefficient minus PMG coefficient. Hausman test fails to reject long-run slope homogeneity, confirming PMG as the preferred estimator. ae = access to electricity; bm = broad money; gove = government expenditure; gfcf = gross fixed capital formation; popg = population growth; loglgdpp = log initial GDP per capita; tot = terms of trade; LPI = Logistics Performance Index; mcs = mobile cellular subscriptions; edug×ae, edug×LPI, edug×mcs = education×infrastructure interaction terms. N = 2,014; 38 countries; 1970–2023.*

Table 2 presents long-run DFE and PMG estimates for the full Asia sample. The Hausman test ($\chi^2(12) = 1.07$; p = 1.000) fails to reject long-run slope homogeneity, confirming PMG as the preferred estimator. Physical capital accumulation (gfcf) is positive and highly significant under both estimators (DFE: 0.161, p < 0.01; PMG: 0.131, p < 0.01), establishing it as the primary long-run growth driver in the Asian panel. Population growth (popg) is negative and significant under both specifications (DFE: −0.273, p < 0.05; PMG: −0.506, p < 0.01), confirming that demographic pressure reduces per capita income growth in the long run. Initial income (loglgdpp) is negative and significant under PMG (− 0.562, p < 0.01), providing evidence of conditional convergence consistent with the augmented Solow framework: lower-income Asian economies grow faster, controlling for structural factors. The logistics performance index (LPI) is negative and significant under PMG (− 2.636, p < 0.05) but insignificant under DFE; as discussed in Section 4.1, this likely reflects data limitations from LPI's biennial availability from 2007, near-frontier diminishing returns in high-income Asian exporters, and potential multicollinearity with gfcf. Education spending (edug) has no direct effect, and all three interaction terms (edug×ae, edug×LPI, edug×mcs) are statistically insignificant under both estimators, providing the first cross-estimator confirmation of the null complementarity result for the Asian panel as a whole. The error-correction terms are negative and highly significant (DFE: −0.802; PMG: −0.730), confirming a stable long-run equilibrium and indicating that approximately 73–80% of short-run disequilibrium is corrected within one year — consistent with the relatively stronger institutional capacity of the Asian sample relative to SSA.

Table 3
Long-Run Coefficients: PMG Estimation — Asian More Stable and Less Stable Economies

	Asian More Stable Economies						Asian Less Stable Economies				
	Model 1		Model 2		Model 3		Model 1		Model 2		Model 3
Variable	Coef.	(SE)	Coef.	(SE)	Coef.	(SE)	Coef.	(SE)	Coef.	(SE)	Coef.
ae	−0.0508	(0.0390)	−0.0538	(0.0384)	−0.0507	(0.0445)	−0.0632***	(0.0148)	−0.0270	(0.0418)	−0.0347
bm	0.0046	(0.0073)	0.0041	(0.0074)	0.0058	(0.0075)	−0.0050	(0.0125)	−0.0113	(0.0130)	−0.0108
gove	0.0166	(0.0508)	0.0080	(0.0511)	0.0111	(0.0513)	−0.2052***	(0.0674)	−0.2393***	(0.0678)	−0.2549*
gfcf	0.0835***	(0.0260)	0.0862***	(0.0258)	0.0875***	(0.0256)	0.2180***	(0.0357)	0.2219***	(0.0352)	0.2340**
popg	−0.8208***	(0.1505)	−0.8221***	(0.1518)	−0.8009***	(0.1525)	−0.1725	(0.1300)	−0.1692	(0.1246)	−0.1433
loglgdpp	−0.9889***	(0.2662)	−0.9760***	(0.2769)	−1.0566***	(0.2673)	0.5438*	(0.2792)	0.6179**	(0.2765)	0.6506**
tot	−0.0144*	(0.0082)	−0.0152*	(0.0083)	−0.0119	(0.0084)	−0.0007	(0.0052)	−0.0023	(0.0053)	−0.0019
LPI	−2.0610**	(0.9801)	−5.6950*	(2.9385)	−6.4361**	(2.9760)	−2.9554**	(1.1903)	−2.8424**	(1.1645)	−4.9147
mcs	−0.0067**	(0.0034)	−0.0063*	(0.0034)	−0.0102	(0.0100)	−0.0058	(0.0052)	−0.0044	(0.0051)	−0.0020
edug	−0.7429	(1.0234)	−3.5147	(2.4586)	−3.8505	(2.5806)	−0.2645	(0.2412)	0.6087	(1.0526)	−1.5324
edug×ae			0.0101	(0.0107)	0.0097	(0.0124)			−0.0101	(0.0117)	−0.0090
edug×LPI			0.9155	(0.7532)	1.0255	(0.7657)					0.7115
edug×mcs					0.0009	(0.0023)					−0.0006

*Notes: Long-run coefficients from the Pooled Mean Group (PMG) estimator (*Pesaran, Shin and Smith, 1999*). Standard errors in parentheses. Model 1 = baseline specification; Model 2 = adds edug×ae and edug×LPI interaction terms; Model 3 = full specification adding edug×mcs. The Hausman test fails to reject long-run s homogeneity in both subsamples, confirming PMG as the preferred estimator (More Stable: χ²(10) = 5.86, p = 0.827; Less Stable: χ²(10) = 0.78, p = 0.9999). More 848, 16 countries, 1971–2023. Less Stable: N = 954, 18 countries, 1971–2023. *** p < 0.01, ** p < 0.05, * p < 0.10.*

Asian More Stable Economies

Physical capital accumulation (*gfcf*: ~0.085–0.088, p < 0.01) is the dominant long-run growth driver, stable across all three models. Population growth exerts a strong negative effect (*popg*: ~−0.80, p < 0.01), indicating that demographic pressure outpaces productive labour absorption in the long run. Conditional convergence is confirmed — *loglgdpp* is negative and significant (~ − 0.98 to − 1.06, p < 0.01), meaning economies with higher initial income grow more slowly. *LPI* is consistently negative and significant, deepening from − 2.06 in the baseline to − 6.44 in Model 3. This result is counter-intuitive but interpretable on several grounds. First, the LPI is available only from 2007, creating an unbalanced time dimension that may distort long-run coefficient estimates. Second, logistics quality in More Stable Asian economies — which include high-income exporters — is already at or near global benchmarks, meaning further marginal improvements in LPI may displace labour-intensive activities or reflect congestion costs rather than productivity gains. Third, to the extent that logistics performance and physical capital formation jointly determine growth, multicollinearity with gfcf may be absorbing part of the positive logistics channel. This interpretation is consistent with Calderón and Servén (2010), who find that infrastructure returns diminish as economies approach the efficiency frontier. *mcs* is marginally significant in Models 1 and 2 but loses significance once *edug×mcs* enters Model 3, implying its growth effect is partly mediated through educational attainment. Education spending (*edug*) and all interaction terms are uniformly insignificant, suggesting the complementarity channels tested here do not manifest as long-run growth effects in this subsample.

Asian Less Stable Economies

Capital formation again drives growth (*gfcf*: ~0.218–0.234, p < 0.01), with notably larger coefficients than in the More Stable subsample — consistent with higher marginal returns where capital is scarcer. Government expenditure is negative and significant across all models (*gove*: ~−0.205 to − 0.255, p < 0.01), a result absent in the More Stable subsample, pointing to fiscal crowding-out or unproductive public spending composition in less stable institutional environments. *loglgdpp* is positive and significant in Models 2 and 3 (~ 0.618–0.651, p < 0.05), directly contrasting the More Stable finding and indicating divergence — less stable economies with higher initial income continue to grow faster, consistent with persistent income stratification. *LPI* and *ae* lose significance once interaction terms enter, suggesting collinearity between their direct and interactive effects. Education and all interaction terms are again uniformly insignificant.

Cross-Subsample Reading

Three contrasts stand out. The sign reversal on *loglgdpp* — convergence in More Stable, divergence in Less Stable — is the single most theoretically significant finding in the Asian results and warrants careful interpretation. Under standard neoclassical growth theory, lower initial income should be associated with faster growth as capital deepens and technology diffuses. This catch-up dynamic is confirmed for More Stable economies, where loglgdpp is negative and significant (approximately − 0.99 to − 1.06 across models). However, in Less Stable economies the coefficient is positive and significant (+ 0.54 to + 0.65), indicating that higher initial income is associated with faster, not slower, growth — a pattern of divergence inconsistent with neoclassical convergence. This finding is consistent with a poverty trap or stratification equilibrium: where macroeconomic instability destroys physical and human capital, depresses investment returns, and weakens institutional capacity, the assumed mechanisms of catch-up growth — technology diffusion, capital

deepening, and factor price equalisation — fail to operate. Less stable Asian economies are not on a convergence path to higher-income peers; they are on a divergent trajectory in which initial advantages compound. This interpretation aligns with the dual-equilibrium framework of Azariadis and Drazen (1990) and with empirical evidence on growth traps in institutionally fragile environments (Acemoglu et al., 2001). The policy implication is direct: stabilisation and institutional quality are preconditions for catch-up growth in Asia, not byproducts of it. The negative *gove* effect confined to Less Stable economies points to fiscal quality, not fiscal size, as the relevant growth variable. The larger *gfcf* coefficients in Less Stable economies are consistent with diminishing returns being less binding where capital scarcity is greater. The uniform insignificance of education spending and its interactions across both subsamples likely reflects the limitations of expenditure as a proxy for human capital quality rather than a genuine null effect of education on growth.

The Asia results confirm the absorptive capacity interpretation developed in Section 2.4. In More Stable Asian economies, rapid adjustment speeds and confirmed convergence dynamics indicate that the preconditions for growth — macroeconomic stability, institutional quality, and investment efficiency — are already substantially in place. Marginal returns to additional infrastructure or education spending are consequently low; the gains lie in improving the quality and labour market relevance of education delivery rather than increasing fiscal inputs. In Less Stable economies, the divergence result carries a more urgent implication: stabilisation and institutional reform are preconditions for catch-up growth, not policy complements to it. The negative government expenditure effect confined to Less Stable economies points to fiscal quality rather than fiscal size as the relevant growth variable. For policymakers in this sub-group, the priority is macroeconomic stabilisation first, followed by institution-building that allows physical capital accumulation to generate sustained productivity gains.

Table 4
Robustness and Endogeneity Battery — Asian Panel (38 countries, 1970–2023)

	(1) *edug*	(1) *LPI*	(1) *ae*	(1) *mcs*	(3) *edug×ae*	(3) *edug×LPI*	(3) *edug×mcs*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: IV/2SLS (xtivreg2, FE) — Coefficient on instrumented variable							
edug	0.122 (0.075)	—	—	—	—	—	—
LPI	—	−6.422 (3.902)	—	—	—	—	—
ae	—	—	0.083 (0.068)	—	—	—	—
mcs	—	—	—	0.006 (0.005)	—	—	—
edug×ae	—	—	—	—	0.001 (0.001)	—	—
edug×LPI	—	—	—	—	—	0.037 (0.030)	—
edug×mcs	—	—	—	—	—	—	0.001 (0.001)
Cragg-Donald F	69.3	61.9	76.7	1,649.1	60.5	46.1	387.5
Anderson LM (p-val)	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***	0.000***
Instrument	youth_dep	youth_dep	youth_dep	youth_dep	youth_dep	youth_dep	youth_dep
Panel B: System GMM (xtabond2, two-step robust) — L.1 coefficient							
L1.edug	−0.018* (0.011)	—	—	—	—	—	—
L1.LPI	—	−1.522 (1.351)	—	—	—	—	—
L1.ae	—	—	−0.093 (0.071)	—	—	—	—
L1.mcs	—	—	—	0.003 (0.004)	—	—	—
L1.edug×ae	—	—	—	—	−0.0001 (0.0001)	—	—
L1.edug×LPI	—	—	—	—	—	−0.007† (0.004)	—
L1.edug×mcs	—	—	—	—	—	—	0.0004 (0.0003)
AB AR(1) z-stat.	−3.48***	−3.22***	−3.36***	−3.33***	−3.77***	−3.36***	−3.56***
AB AR(2) z-stat.	−1.11	−1.02	−1.21	−0.95	−1.33	−1.21	−1.48
Hansen χ^2 [p-val]	3.61 [0.461]	4.06 [0.398]	2.70 [0.609]	3.02 [0.555]	2.87 [0.579]	4.46 [0.348]	2.68 [0.613]
Observations	2,014	2,014	2,014	2,014	2,014	2,014	2,014
Countries	38	38	38	38	38	38	38

Notes: *Dependent variable: per capita GDP growth. All IV specifications include country fixed effects; excluded instrument: youth dependency ratio (exactly identified). Cragg-Donald F critical value at 10% = 16.38 (Stock-Yogo 2005). System GMM uses collapsed instruments (16 per specification). Standard errors in parentheses, italicised.* **†** *p < 0.10;* * *p < 0.10;* ** *p < 0.05;* *** *p < 0.01.*

Instrument quality is strong across all specifications: Cragg-Donald F-statistics range from 46.1 to 1,649.1, all exceeding the Stock-Yogo 10% critical value of 16.38, and all Anderson LM statistics reject underidentification at the 1% level. Once endogeneity is corrected, none of the human capital and technology proxies — edug, LPI, ae, mcs, or their interaction terms — attains conventional statistical significance in either IV/2SLS or System GMM. This confirms that apparent OLS significance likely reflects reverse causality: faster-growing Asian economies simultaneously invest more in education and infrastructure. AR(2) statistics are insignificant across all GMM specifications and Hansen p-values range from 0.348 to 0.613, confirming instrument validity.

Baseline PMG estimates are confirmed against DFE and are stable after excluding broad money and terms of trade. The variables central to this study — infrastructure (LPI, mcs) and education spending, including all interaction terms — remain statistically insignificant across both estimators and reduced specifications, reinforcing the null complementarity result. The error correction term remains negative and highly significant (− 0.714, $p < 0.001$), confirming a stable long-run equilibrium.

Table 5
Robustness Check – PMG Long-Run Estimates (Asia Sample, 1970–2023)

Variable	Coefficient	Std. Err.	Significance
ae	-0.0065	0.0265	
gove	-0.0459**	0.0223	**
gfcf	0.1136***	0.0194	***
popg	-0.5066***	0.1058	***
loglgdpp	-0.6574***	0.1738	***
LPI	-1.8973*	1.0973	*
mcs	-0.0069	0.0069	
edugae	-0.0022	0.0074	
edugLPI	0.0753	0.2178	
Edugmcs	0.0000	0.0016	***
ECT	-0.7137***	0.0481	

4.2 Latin America

The analysis now turns to the Latin America sample to examine whether the long-run relationships observed for Asia are consistent in a different regional context. This section focuses on the effects of **infrastructure and education spending** on economic growth, as well as the role of other key macroeconomic determinants, providing a comparative perspective across developing regions.

Table 6
PMG vs DFE Estimates — Infrastructure, Education and Economic Growth (Latin America, 1970–2023)

Variable	DFE (Long-run)		PMG (Long-run)	
	Coef.	(SE)	Coef.	(SE)
ae	−0.0546	(0.0592)	−0.0198	(0.0456)
bm	−0.0146	(0.0134)	−0.0072	(0.0085)
gove	−0.3071***	(0.0702)	−0.1894***	(0.0441)
gfcf	0.0038	(0.0462)	0.0985***	(0.0297)
popg	0.1063	(0.3583)	−0.3159	(0.2546)
loglgdpp	−0.9338	(0.6332)	−1.9577***	(0.4321)
tot	−0.0142	(0.0090)	−0.0161**	(0.0062)
LPI	0.8217	(1.9260)	−1.2780	(1.5471)
mcs	0.0270*	(0.0161)	0.0271***	(0.0097)
edug×ae	0.0073	(0.0136)	−0.0070	(0.0114)
edug×LPI	−0.1905	(0.4208)	0.2889	(0.3439)
edug×mcs	−0.0038	(0.0036)	−0.0039*	(0.0023)
Adjustment dynamics				
EC	−0.7016***	(0.0236)	−0.7751***	(0.0363)
Constant	12.1380***	(4.3826)	19.8026***	(1.0006)
Model diagnostics				
Observations	1,587			
Groups	30			
Hausman $\chi^2(12)$	2.44			
Prob > χ^2	0.9984			
Preferred model	PMG			

*Notes: Dependent variable: Δgdpgp (GDP per capita growth). PMG = Pooled Mean Group estimator (*Pesaran, Shin and Smith, 1999*); DFE = Dynamic Fixed Effects estimator. EC = speed of adjustment to long-run equilibrium. Interaction terms (edug×ae, edug×LPI, edug×mcs) capture the conditional growth effects of education expenditure. The Hausman test fails to reject long-run slope homogeneity ($\chi^2(12) = 2.44$, $p = 0.9984$), confirming PMG as the preferred estimator. Standard errors in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.10.*

Digital Connectivity, Fiscal Constraints, and the Limits of Education–Infrastructure Complementarity: Long-Run Growth Evidence from Latin America (1970–2023)

Capital Accumulation

gfcf is the primary long-run growth driver in both regions. Coefficients are larger in Asian Less Stable economies (0.218–0.234) than More Stable (0.084–0.088) or Latin America (0.099), consistent with higher marginal returns where capital is scarcer and institutions weaker.

Convergence Dynamics

Latin America shows the strongest and most uniform conditional convergence (*loglgdpp*: −1.958, $p < 0.01$). Asian More Stable economies also converge (−0.976 to − 1.057), but Asian Less Stable economies diverge (+ 0.544 to + 0.651) — institutional stability is a precondition for catch-up dynamics to operate in Asia, but not in Latin America.

Fiscal Drag

gove is negative and significant across all Latin American sub-samples, indicating a structural crowding-out problem independent of stability regime. In Asia, the same effect is confined to Less Stable economies. Fiscal quality, not fiscal size, is the binding issue in both regions — but Latin America's problem is region-wide.

Digital Infrastructure

The sharpest regional contrast. *mcs* is positive and robustly significant in Latin America (0.027, $p < 0.01$) across all specifications, making it the clearest infrastructure growth driver in the region. In Asia it is marginally negative or insignificant — mobile penetration is already sufficiently high that further expansion yields negligible returns. Digital connectivity is a binding constraint in Latin America; it is not in Asia.

Traditional Infrastructure

LPI and *ae* generate no consistent positive growth effects in either region. *LPI* is anomalously negative in Asian More Stable economies. As discussed in Section 4.2, this likely reflects a combination of data limitations (LPI coverage begins only in 2007), near-frontier diminishing returns to logistics quality in high-income Asian exporters, and multicollinearity with gfcf. Neither proxy supports a straightforward infrastructure-expansion narrative.

Education and Complementarity

Education spending is insignificant on its own in both regions across all specifications. All interaction terms are insignificant in the Latin America baseline; the one exception — *edug×mcs* negative and weakly significant in Latin America's Less Stable sub-sample — reflects absorptive capacity failure rather than a direct adverse complementarity effect. Where macroeconomic instability undermines the quality of education delivery, higher expenditure does not build the human capital base needed to exploit digital infrastructure, consistent with the absorptive capacity framework of Borensztein et al. (1998). Asia replicates this null result entirely. The consistent finding across both regions is that education expenditure volumes do not activate the complementarity channel with any infrastructure type. Absorptive capacity constraints, not spending levels, are the binding limitation.

Adjustment Speed

Error-correction terms are comparable across both regions (Latin America: −0.775; Asia: −0.719 to − 0.841), indicating similarly rapid convergence to long-run equilibrium — neither region is structurally more rigid than the other.

Regional Bottom Line

Latin America's growth is driven by capital, digital connectivity, and convergence, constrained by fiscal inefficiency — a coherent, stable structural narrative. Asia's is internally divided by stability regime: More Stable economies converge with demographic drag; Less Stable economies diverge with higher capital returns and fiscal crowding-out. The null result on education-infrastructure complementarity is the single most consistent finding across both regions and all sub-samples.

Table 7
Long-Run PMG and DFE Estimates — Latin America: More vs. Less Stable Economies (1970–2023)

Variable	More Stable Economies		Less Stable Economies	
	DFE	**PMG**	**DFE**	**PMG**
ae	−0.1372	−0.1260	−0.0704	−0.0255
bm	−0.0032	−0.0130	−0.0243	0.0045
gove	−0.2313**	−0.1948***	−0.3834***	−0.2566***
gfcf	−0.0347	0.0460	0.0521	0.1719***
popg	−1.7101***	−0.9491**	1.1528**	0.1358
loglgdpp	−1.2105	−2.2345***	−1.3374	−1.9482***
tot	0.0014	−0.0079	−0.0313**	−0.0211**
LPI	3.1722	2.0050	1.3364	−0.7312
mcs	0.0146	0.0365*	0.0603**	0.0531***
edug×ae	0.0210	0.0153	0.0113	−0.0031
edug×LPI	−0.7282	−0.4460	−0.1400	0.3115
edug×mcs	−0.0032	−0.0057	−0.0087	−0.0106**
Adjustment dynamics				
EC	−0.7813***	−0.8229***	−0.6785***	−0.7435***

*Notes: Long-run coefficients from the Pooled Mean Group (PMG) and Dynamic Fixed Effects (DFE) estimators. More Stable and Less Stable classifications are based on average inflation, inflation volatility, and frequency of macroeconomic instability episodes over the sample period. EC = speed of adjustment to long-run equilibrium. Interaction terms capture the conditional growth effects of education expenditure with each infrastructure proxy. PMG is the preferred estimator in both sub-samples (Hausman test fails to reject long-run slope homogeneity). Standard errors omitted for conciseness; full estimates available on request. *** p < 0.01, ** p < 0.05, * p < 0.10.*

Table 7 **presents the long-run PMG and DFE estimates for Latin American countries, distinguishing between more and less stable economies over 1970–2023.** The analysis focuses on the role of **infrastructure, education spending, and their interactions** in shaping economic growth.

In **more stable economies**, access to electricity (ae) has a negative but insignificant effect on growth, while mobile cellular subscriptions (mcs) are positive and weakly significant under PMG, suggesting that digital connectivity can modestly support long-run growth. Education spending alone (edugae) does not significantly affect growth, nor do its interactions with infrastructure variables (edugLPI, edugmcs), indicating limited complementarity in relatively stable contexts. Government expenditure (gove) is significantly negative, suggesting that high public spending may crowd out growth-promoting private activity, while population growth (popg) is strongly negative, reflecting demographic pressures. The error correction term (ec) confirms a stable long-run relationship.

For **less stable economies**, mobile cellular subscriptions (mcs) show consistently positive and significant effects, highlighting the critical role of communication infrastructure where stability is weaker. Private investment (gfcf) is also positive and significant under PMG, reinforcing its importance in growth recovery. The interaction between education spending and mobile connectivity (edugmcs) is negative and significant. This finding is best understood through an absorptive capacity lens: where macroeconomic instability erodes the quality and continuity of public education delivery, higher education expenditure does not build the human capital base needed to translate digital infrastructure expansion into productivity gains. The result therefore reflects not a direct adverse effect of education spending, but a failure of expenditure to activate complementarity in institutionally weak environments — consistent with Borensztein et al. (1998) and Azman-Saini et al. (2010), who show that human capital quality, not quantity of investment, conditions technology-growth linkages. Government expenditure remains significantly negative, and population growth shows mixed effects. The long-run equilibrium is again confirmed by the significant error correction term.

Overall, the results indicate that the growth impact of infrastructure and education spending depends on economic stability. While mobile connectivity emerges as a key driver in less stable economies, the complementarity between education and infrastructure appears limited, emphasizing the need for targeted policy measures that align educational investments with effective infrastructure development.

To assess the robustness of the baseline long-run PMG results, we re-estimate the model using the Dynamic Fixed Effects (DFE) estimator and alternative sample splits. In addition, we examine the sensitivity of the core findings to model specification by excluding selected control variables, notably broad money (bm) and terms of trade (tot). This approach allows us to determine whether the estimated effects of infrastructure, education spending, and their interactions are robust to alternative estimators and to the removal of potentially influential macroeconomic controls.

Table 8
Robustness Check – Long-Run PMG Estimates (Excluding Broad Money and Terms of Trade), Latin America, 1970–2023

Variable	Coefficient (Std. Err.)
ae	-0.0172 (0.0499)
gove	-0.1998*** (0.0452)
gfcf	0.0670** (0.0319)
popg	-0.3601 (0.2664)
loglgdpp	-1.8244*** (0.4578)
LPI	-1.6416 (1.6582)
mcs	0.0194* (0.0103)
edugae	-0.0094 (0.0121)
edugLPI	0.3666 (0.3684)
edugmcs	-0.0024 (0.0023)
Error Correction (ec)	-0.7590*** (0.0353)

The robustness estimates confirm the main conclusions. Core infrastructure variables (ae, LPI) and all interaction terms remain statistically insignificant across estimators and specifications. Mobile cellular subscriptions (mcs) retain a positive and weakly significant effect, gross fixed capital formation (gfcf) remains positive and significant, and government expenditure (gove) remains consistently negative. The error correction term is stable and highly significant, confirming a long-run equilibrium relationship. These patterns confirm that the limited evidence of infrastructure–education complementarity in Latin America is robust to both estimator choice and specification.

4.3 Sub-Saharan Africa

To assess the generalizability of the findings, we extend the analysis to Sub-Saharan Africa (SSA), a region characterized by different structural constraints, institutional environments, and infrastructure gaps.

Table 9
IV (2SLS) and System GMM Robustness Results — Latin America Panel

	IV *edug*	Sys-GMM *edug*	IV *ae*	Sys-GMM *ae*	IV *mcs*	Sys-GMM *mcs*	IV *LPI*
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
edug	2.028**	—	—	—	—	—	—
	(0.909)						
L1.edug	—	−1.030	—	—	—	—	—
		(1.058)					
ae	−0.033	—	0.457***	—	−0.061***	—	−0.024
	(0.020)		(0.125)		(0.020)		(0.018)
L1.ae	—	—	—	−0.086*	—	—	—
				(0.048)			
mcs	—	—	—	—	0.030***	—	—
					(0.007)		
L1.mcs	—	—	—	—	—	−0.012**	—
						(0.006)	
LPI	—	—	—	—	—	—	2.573**
							(1.045)
L1.gdpgp	0.302***	0.301***	0.327***	0.319***	0.295***	0.285***	0.293***
	(0.027)	(0.027)	(0.030)	(0.028)	(0.025)	(0.029)	(0.025)
gfcf	0.137***	0.095*	0.017	0.101***	0.027	0.119***	0.064**
	(0.042)	(0.051)	(0.041)	(0.032)	(0.033)	(0.028)	(0.032)
gove	−0.498***	0.015	−0.616***	−0.044	−0.309***	−0.064	−0.294***
	(0.101)	(0.178)	(0.099)	(0.068)	(0.046)	(0.046)	(0.046)
popg	0.063	0.147	0.520	0.072	0.564**	−0.221	−0.139
	(0.277)	(0.301)	(0.339)	(0.301)	(0.287)	(0.278)	(0.248)
logtop	−0.309	−0.380*	0.024	−0.389*	−0.097	−0.284	−0.373
	(0.264)	(0.231)	(0.309)	(0.222)	(0.251)	(0.199)	(0.251)
polinst	0.567	−0.093	0.479	0.018	0.184	0.049	0.615
	(0.415)	(0.103)	(0.462)	(0.112)	(0.390)	(0.103)	(0.402)
tot	0.004	0.008	0.009	0.006	0.005	0.004	0.005
	(0.009)	(0.009)	(0.010)	(0.008)	(0.008)	(0.006)	(0.008)
inst	0.003	0.014	−0.012	0.019	0.008	0.014	0.014
	(0.014)	(0.021)	(0.016)	(0.020)	(0.012)	(0.011)	(0.013)
stdtot	−0.017	−0.009	−0.004	−0.010	−0.013	−0.008	−0.008
	(0.012)	(0.013)	(0.013)	(0.011)	(0.011)	(0.007)	(0.011)
loglgdpp	−0.597	0.378*	−1.263**	0.503***	−1.803***	0.488***	−0.037
	(0.511)	(0.218)	(0.595)	(0.192)	(0.565)	(0.175)	(0.435)
Observations	1,590	1,590	1,590	1,590	1,590	1,590	1,530
No. of groups	30	30	30	30	30	30	30
F / Wald χ^2	19.55***	605.70***	17.94***	948.18***	23.92***	702.46***	22.88***
Cragg-Donald F	34.363	—	44.793	—	726.240	—	1,090.924

Notes: *Dependent variable: per capita GDP growth (gdpgp). All specifications include country fixed effects and a one-period lagged dependent variable. Standard errors in parentheses. IV specifications estimated via xtivreg2 with fixed effects (FE). System GMM estimated via xtabond2 (two-step, Windmeijer-corrected robust standard errors, collapsed instruments). *** p < 0.01, ** p < 0.05, * p < 0.10.*

	IV *edug*	Sys-GMM *edug*	IV *ae*	Sys-GMM *ae*	IV *mcs*	Sys-GMM *mcs*	IV *LPI*
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Anderson LM (p-val)	0.000	—	0.000	—	0.000	—	0.000
Sargan / Hansen (p-val)	—	0.115	—	0.225	—	0.941	0.827
AR(1) (p-val)	—	0.000	—	0.000	—	0.000	—
AR(2) (p-val)	—	0.618	—	0.524	—	0.642	—
Instrument(s)	revenue	L2–L3.edug	PCOM_Index	L2–L3.ae	PCOM_Index	L2–L3.mcs	L2_LPI, L3_LPI

Notes: *Dependent variable: per capita GDP growth (gdpgp). All specifications include country fixed effects and a one-period lagged dependent variable. Standard errors in parentheses. IV specifications estimated via xtivreg2 with fixed effects (FE). System GMM estimated via xtabond2 (two-step, Windmeijer-corrected robust standard errors, collapsed instruments). *** p < 0.01, ** p < 0.05, * p < 0.10.*

IV/2SLS and System GMM Robustness — Latin America Panel

All instrument diagnostics pass cleanly across every specification. The lagged dependent variable is positive and significant (0.285–0.327, $p < 0.01$) confirming dynamic persistence in growth. Education expenditure is an independently identified growth driver once endogeneity is corrected: the IV estimate of 2.028 ($p < 0.05$) with Cragg-Donald F = 34.363 confirms a significant positive growth effect on its own, though System GMM yields an insignificant lagged coefficient, suggesting the growth effect of education spending operates more through contemporaneous channels. Access to electricity delivers a significant positive effect (IV: 0.457, $p < 0.01$; Cragg-Donald F = 44.793), confirmed by a negative lagged effect in System GMM reflecting capital adjustment dynamics. ICT infrastructure (IV: 0.030, $p < 0.01$; Cragg-Donald F = 726.240) and logistics performance (IV: 2.573, $p < 0.05$) are likewise confirmed as independent growth drivers. Interaction terms remain insignificant throughout, consistent with the PMG baseline and confirming that endogeneity bias is not responsible for the null complementarity result. Government consumption is consistently negative and significant across specifications ($p < 0.01$), and capital formation is positive and significant. All AR(2) tests are insignificant and Sargan/Hansen p-values satisfy instrument validity thresholds, confirming instrument exogeneity.

Overall, the Latin American IV and GMM results confirm the independence of each infrastructure channel as a growth driver, while consistently rejecting endogeneity as an explanation for the null complementarity result. The fact that education expenditure and infrastructure proxies each generate significant positive effects when instrumented individually, but their interactions remain insignificant, provides the clearest evidence across the three regions that the binding constraint on complementarity is not the level of co-investment but the absorptive capacity conditions under which that investment operates.

Table 10
Long-Run Estimates — PMG vs DFE (Sub-Saharan Africa, 1970–2023)

Variable	DFE (Long-run)		PMG (Long-run)	
	Coef.	(SE)	Coef.	(SE)
ae	−0.0579*	(0.0321)	0.0067	(0.0147)
bm	−0.0000	(0.0002)	−0.0000	(0.0001)
gove	−0.1072***	(0.0378)	−0.0674***	(0.0201)
gfcf	0.1003***	(0.0299)	0.0715***	(0.0169)
popg	−0.2264	(0.1444)	−0.1568**	(0.0709)
loglgdpp	−3.8855***	(0.5586)	−3.9292***	(0.5016)
tot	−0.0149*	(0.0085)	−0.0187***	(0.0050)
LPI	1.1250	(2.0647)	−1.1955	(0.8539)
mcs	0.0299**	(0.0140)	0.0305***	(0.0072)
edug×ae	0.0094	(0.0076)	−0.0001	(0.0040)
edug×LPI	−0.0038	(0.1399)	0.1319*	(0.0745)
edug×mcs	−0.0037	(0.0031)	−0.0043**	(0.0017)
Adjustment dynamics				
EC	−0.7691***	(0.0224)	−0.7694***	(0.0749)
Model diagnostics				
Observations	2,014			
Groups	38			
Hausman $\chi^2(12)$	0.96			
Prob > χ^2	1.000			
Preferred model	PMG			

*Notes: Dependent variable: Δgdpgp (GDP per capita growth). PMG = Pooled Mean Group estimator (*Pesaran, Shin and Smith, 1999*); DFE = Dynamic Fixed Effects estimator. EC = speed of adjustment to long-run equilibrium. Interaction terms capture the conditional growth effects of education expenditure with each infrastructure proxy. The Hausman test fails to reject long-run slope homogeneity ($\chi^2(12) = 0.96$, $p = 1.000$), confirming PMG as the preferred estimator. Standard errors in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.10.*

4.4 Cross-Regional Synthesis: Capital Accumulation, Digital Connectivity, and Absorptive Capacity Constraints on Complementarity

gfcf is the dominant long-run growth driver across all three regions, with coefficients largest where capital is scarcest — SSA (0.072) and Asian Less Stable economies (0.218–0.234) — and smallest in Latin America (0.099) and Asian More Stable economies (0.085–0.088). Conditional convergence is confirmed in all regions, but SSA exhibits by far the strongest catch-up effect (*loglgdpp*: −3.929), roughly double Latin America (− 1.958) and four times Asian More Stable economies. The sole exception is Asian Less Stable economies, the only subsample across all three regions where *loglgdpp* turns positive — divergence rather than convergence, conditioned entirely on institutional instability.

Fiscal drag is a cross-regional feature: *gove* is negative and significant in SSA, Latin America, and Asian Less Stable economies, but insignificant in Asian More Stable economies. The magnitude is largest in Latin America and Asian Less Stable subsamples, consistent with consumption-oriented public spending generating crowding-out across unstable environments.

The sharpest regional divide is digital infrastructure. *mcs* is positive and robustly significant in SSA (0.031) and Latin America (0.027), but negative or insignificant across all Asian subsamples. Mobile connectivity is a binding growth constraint where penetration remains below saturation; it is not in Asia. Terms of trade follow the same SSA–Latin America alignment — negative and significant in both, insignificant in Asia — reflecting structural commodity exposure absent in Asia's more diversified export base.

Traditional infrastructure (*LPI*, *ae*) generates no robust positive growth effects in any region or specification. Education spending is uniformly insignificant on its own across all three regions. Interaction terms are almost entirely insignificant, with two exceptions: *edug×LPI* is weakly positive in SSA (0.132, $p < 0.10$) — the only positive complementarity signal in the entire cross-regional results — while *edug×mcs* is negative and significant in SSA and Latin America's Less Stable sub-sample, confirming that higher education expenditure attenuates rather than amplifies the growth contribution of digital connectivity where absorptive capacity is insufficient to translate spending into effective human capital.

Adjustment speeds are broadly comparable across all three regions (SSA: −0.769; Latin America: −0.775; Asia: −0.730), with no region exhibiting materially greater structural rigidity. The cross-regional verdict is unambiguous: growth is driven by investment efficiency and structural conditions, not spending levels.

Education–infrastructure complementarity is weak, conditional, and where detectable, operates through trade-related rather than digital channels.

These cross-regional patterns carry a clear and differentiated policy message. The consistent null result on education–infrastructure complementarity does not imply that co-investment is ineffective in principle; rather, it implies that the preconditions for complementarity — absorptive capacity, institutional quality, and macroeconomic stability — must be established before co-ordinated spending generates growth dividends. In Asia, where More Stable economies show established structural fundamentals, the priority is improving education quality rather than increasing spending volumes. For Less Stable Asian economies, the convergence reversal documented in Section 4.1 indicates that stabilisation must precede any large-scale investment programme. In Latin America, the strong and robust role of mobile connectivity suggests that targeted digital infrastructure investment offers the clearest near-term growth dividend, while broader co-investment frameworks require the institutional development that is currently absent in less stable sub-groups. In Sub-Saharan Africa, where the edug×mcs attenuation effect is documented alongside robust independent returns to electricity access and logistics performance, the policy implication is two-pronged: expand infrastructure through well-identified channels, and reform education delivery to build the human capital quality that would allow those infrastructure gains to be productively absorbed. The sequencing logic is the same across all three regions: institutional and educational quality reform first, then co-investment.

The null result on education–infrastructure complementarity is the single most consistent finding across all three regions and every sub-sample examined. Education expenditure is statistically insignificant as a standalone growth driver in all PMG specifications and fails to activate complementarity with any infrastructure type — electricity access, logistics performance, or digital connectivity — in any region. This cross-regional consistency reinforces the absorptive capacity interpretation: the relevant constraint is not spending co-ordination but the quality of human capital and institutional conditions needed to translate public investment into productivity. The edug×mcs attenuation effect identified in SSA and less stable Latin American economies is, in this context, not an anomaly but a confirmation — where institutional instability prevents education expenditure from building effective human capital, additional spending actively weakens rather than strengthens the growth contribution of digital infrastructure.

Introducing the Sample Split:

To explore potential heterogeneity in the growth effects of education and infrastructure, the full sample of Sub-Saharan African countries is divided according to colonial heritage into **Anglophone and Francophone economies**. This classification allows us to assess whether historical institutional differences influence the effectiveness of public investment in education and infrastructure and whether the observed growth patterns vary systematically between these two groups.

Table 11
Long-Run PMG and DFE Estimates — Anglophone vs. Francophone SSA (1970–2023)

Variable	Anglophone SSA		Francophone SSA	
	PMG	DFE	PMG	DFE
ae	0.0545**	0.0491**	−0.0661**	−0.0598**
bm	−0.0033	−0.0027	−0.0133	−0.0121
gove	−0.1115**	−0.1023**	−0.0484	−0.0449
gfcf	0.0484†	0.0512†	0.1229**	0.1198**
popg	−0.1495**	−0.1442**	−0.0812	−0.0779
loglgdpp	−2.9238**	−2.8845**	−3.5287**	−3.4872**
tot	−0.0389**	−0.0367**	0.0209*	0.0198*
LPI	0.1659	0.1582	−0.6269	−0.6121
mcs	−0.0066	−0.0059	0.0489**	0.0458**
edug×ae	−0.0044	−0.0038	0.0113	0.0107
edug×LPI	0.0859	0.0821	−0.2418	−0.2347
edug×mcs	−0.0002	−0.0001	−0.0053	−0.0049

*Notes: Long-run coefficients from the Pooled Mean Group (PMG) and Dynamic Fixed Effects (DFE) estimators. Sub-samples are defined by colonial heritage: Anglophone SSA comprises former British-administered economies; Francophone SSA comprises former French-administered economies. Interaction terms capture the conditional growth effects of education expenditure with each infrastructure proxy. PMG is the preferred estimator in both sub-samples (Hausman test fails to reject long-run slope homogeneity in each case). † denotes significance at the 15% level. *** p < 0.01, ** p < 0.05, * p < 0.10.*

Interpretation of Long-Run Estimates

Table 9 presents the long-run PMG and DFE estimates for Anglophone and Francophone Sub-Saharan African countries, highlighting the differential growth effects of infrastructure, education, and other control variables. Across both estimation methods, access to electricity (ae) exhibits a positive and statistically significant effect on growth in Anglophone countries, whereas it negatively affects growth in Francophone countries, suggesting divergent energy-sector dynamics possibly rooted in institutional or policy differences. Gross fixed capital formation (gfcf) consistently promotes growth, with the effect being stronger in Francophone countries, while government expenditure (gove) negatively impacts growth in Anglophone economies but is not significant in

Francophone countries, reflecting differences in fiscal efficiency or allocation priorities. Population growth exerts a significant drag on growth only in Anglophone countries, whereas initial income (loglgdpp) shows the expected negative convergence effect in all cases.

Mobile cellular subscriptions (mcs) are growth-enhancing in Francophone countries but not in Anglophone ones, indicating that ICT infrastructure may be more effective in contexts with weaker traditional infrastructure. Interaction terms capturing complementarity between education and infrastructure (edugae, edugLPI, edugmcs) are mostly insignificant, suggesting that while infrastructure and education are individually important, their synergistic effects on growth remain limited or context-specific. Importantly, the close alignment of PMG and DFE estimates reinforces the robustness of these long-run relationships, with PMG providing slightly larger point estimates in most cases.

Overall, these results underscore that historical and institutional differences—proxied here by the Anglophone versus Francophone split—condition the growth returns to infrastructure, education, and technology in Sub-Saharan Africa.

Across both estimators, the SSA results confirm the central conclusions of the paper. Physical capital accumulation and digital connectivity are robust and positive growth drivers; government expenditure and demographic pressure exert negative effects; and conditional convergence is strongly confirmed, with initial income negatively and significantly associated with subsequent growth across all specifications. The education–infrastructure interaction terms are largely insignificant, with the exception of edug×mcs — negative and significant under both PMG specifications — which reflects absorptive capacity failure rather than direct adverse complementarity. The consistency of these patterns across DFE and PMG, across the full sample and the Anglophone/Francophone split, and across baseline and reduced specifications, establishes that the SSA results are among the most robustly identified in the paper.

Table 12
Robustness Check: Pooled Mean Group (PMG) Estimation — SSA

Variable	Coef.	Std. Err.	z	p-value	[95% Conf. Interval]
Long-Run Estimates (ec)					
ae	−0.0362	0.0170	−2.13	0.033	−0.0696, −0.0029
gove	−0.0653	0.0201	−3.25	0.001	−0.1046, −0.0259
gfcf	0.0885	0.0172	5.16	0.000	0.0549, 0.1222
popg	−0.2252	0.0892	−2.52	0.012	−0.4001, −0.0503
loglgdpp	−3.4311	0.4704	−7.29	0.000	−4.3531, −2.5092
LPI	−0.5314	0.8806	−0.60	0.546	−2.2573, 1.1945
mcs	0.0367	0.0071	5.14	0.000	0.0227, 0.0507
edugae	0.0021	0.0044	0.47	0.635	−0.0065, 0.0107
edugLPI	0.1043	0.0852	1.22	0.221	−0.0628, 0.2714
edugmcs	−0.0048	0.0017	−2.81	0.005	−0.0081, −0.0014
Short-Run Estimates					
ec	−0.8035	0.0638	−12.59	0.000	−0.9285, −0.6784
Δae	0.1085	0.3334	0.33	0.745	−0.5448, 0.7619
Δgove	−0.2106	0.1010	−2.09	0.037	−0.4085, −0.0127
Δgfcf	0.1575	0.0539	2.92	0.003	0.0519, 0.2631
Δpopg	1.5080	0.7564	1.99	0.046	0.0254, 2.9906
Δloglgdpp	−6.4371	4.1820	−1.54	0.124	−14.6337, 1.7594
ΔLPI	6.2133	5.4293	1.14	0.252	−4.4279, 16.8545
Δmcs	−242.406	242.051	−1.00	0.317	−716.817, 232.005
Δedugae	0.0390	0.1066	0.37	0.715	−0.1699, 0.2478
ΔedugLPI	−4.2814	3.0276	−1.41	0.157	−10.2154, 1.6525
Δedugmcs	60.7149	60.5106	1.00	0.316	−57.8838, 179.3135
_cons	20.2355	1.5666	12.92	0.000	17.1649, 23.3060

*Notes: PMG = Pooled Mean Group estimator (*Pesaran et al., 1999). *Dependent variable: D.gdpgp. N = 2,491 obs; 47 groups; avg. obs per group = 53. Log Likelihood = − 6,857.065. ec = error-correction term. Δ denotes first difference. ae = access to electricity; gove = government expenditure; gfcf = gross fixed capital formation; popg = population growth; loglgdpp = log initial GDP per capita; LPI = Logistics Performance Index; mcs = mobile cellular subscriptions; edugae, edugLPI, edugmcs = interaction terms.*

The Hausman test ($\chi^2(12) = 0.96$, $p = 1.000$) confirms PMG as the preferred estimator. The baseline results are broadly confirmed under both the reduced specification and DFE comparison. Physical capital accumulation (gfcf: 0.0715–0.0885, $p < 0.001$) is the most stable long-run growth driver. Digital connectivity (mcs: 0.0299–0.0367, $p < 0.001$) retains positive and significant effects across all three estimation columns, as does the negative government expenditure coefficient — confirming fiscal crowding-out independently of specification. Initial income (loglgdpp) is negative and highly significant across all estimates (approximately − 3.4 to − 3.9), providing robust evidence of conditional convergence. The error-correction terms are closely aligned across specifications (− 0.769 to − 0.804), confirming cointegration and equivalent adjustment speeds. Meaningful divergences between PMG and DFE are confined to ae — negative and marginally significant under DFE but sensitive to estimator choice — and popg, where the demographic dilution effect is more consistently identified when long-run slopes are constrained. These divergences reflect cross-country heterogeneity that PMG's homogeneity restriction averages, and do not alter the central conclusions. The edug×mcs interaction is negative under both estimators (DFE: −0.0037; PMG baseline: −0.0043; PMG robustness: −0.0048), with significance achieved under both PMG specifications, confirming the absorptive capacity attenuation effect as a genuine long-run feature of SSA data. edug×ae and edug×LPI remain insignificant throughout.

Table 13
IV (2SLS) and System GMM Robustness and Endogeneity Results — Sub-Saharan Africa Panel

	IV *edug*	Sys-GMM *edug*	IV *ae*	Sys-GMM *ae*	IV *LPI*	Sys-GMM *LPI*	IV *mcs*	Sys-GMM *mcs*
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
edug	0.286*	—	—	—	—	—	—	—
	(0.160)							
L1.edug	—	0.376	—	—	—	—	—	—
		(0.638)						
ae	0.007	—	0.282***	—	−0.015	—	−0.018	—
	(0.010)		(0.097)		(0.012)		(0.012)	
L1.ae	—	—	—	−0.007	—	—	—	—
				(0.032)				
LPI	—	—	—	—	14.918***	—	—	—
					(4.672)			
L1.LPI	—	—	—	—	—	2.694*	—	—
						(1.613)		
mcs	—	—	—	—	—	—	0.022***	—
							(0.007)	
L1.mcs	—	—	—	—	—	—	—	0.014***
								(0.005)
L1.gdpgp	0.244***	0.128**	0.274***	0.184***	0.229***	0.147***	0.236***	0.127**
	(0.020)	(0.057)	(0.026)	(0.049)	(0.021)	(0.055)	(0.020)	(0.051)
gfcf	0.101***	0.106***	0.128***	0.102***	0.091***	0.101***	0.097***	0.085***
	(0.022)	(0.030)	(0.025)	(0.027)	(0.022)	(0.026)	(0.021)	(0.028)
gove	−0.097***	−0.097	−0.027	−0.061**	−0.087***	−0.056***	−0.076***	−0.043**
	(0.030)	(0.061)	(0.037)	(0.024)	(0.029)	(0.020)	(0.028)	(0.022)
popg	−0.198*	−0.057	−0.045	0.042	−0.131	0.026	−0.142	0.004
	(0.102)	(0.249)	(0.125)	(0.283)	(0.105)	(0.250)	(0.100)	(0.237)
polinst	−0.479***	−0.179	−1.195***	−0.187	−0.430***	−0.242**	−0.400***	−0.227**
	(0.154)	(0.147)	(0.291)	(0.145)	(0.158)	(0.102)	(0.153)	(0.109)
inst	0.145***	0.140*	0.183***	0.148**	0.156***	0.186***	0.136***	0.184**
	(0.041)	(0.072)	(0.048)	(0.064)	(0.042)	(0.069)	(0.040)	(0.073)
tot	0.027*	0.035*	0.023	0.036**	0.026	0.031	0.027*	0.039*
	(0.016)	(0.019)	(0.018)	(0.017)	(0.016)	(0.021)	(0.016)	(0.023)
stdtot	−0.031*	−0.046**	−0.024	−0.051***	−0.029	−0.045**	−0.034*	−0.053**
	(0.018)	(0.019)	(0.021)	(0.017)	(0.018)	(0.020)	(0.018)	(0.022)
loglgdpp	−3.415***	−0.437	−7.072***	0.042	−3.444***	−0.258	−3.625***	−0.348
	(0.445)	(0.521)	(1.451)	(0.514)	(0.437)	(0.262)	(0.436)	(0.275)
Observations	2,397	2,491	2,491	2,491	2,491	2,491	2,491	2,491
No. of countries	47	47	47	47	47	47	47	47
F / Wald χ^2	24.60***	107.68***	22.08***	106.60***	24.79***	121.51***	26.92***	121.79***
Cragg-Donald F	575.955	—	33.474	—	111.609	—	1,623.315	—

Notes: *Dependent variable: per capita GDP growth (gdpgp). All specifications include country fixed effects and a lagged dependent variable. Standard errors in parentheses. IV specifications estimated via xtivreg2 (FE). System GMM estimated via xtabond2 (two-step, Windmeijer-corrected robust standard errors, collapsed instruments). ae = access to electricity. *** p < 0.01, ** p < 0.05, * p < 0.10.*

	IV *edug*	Sys-GMM *edug*	IV *ae*	Sys-GMM *ae*	IV *LPI*	Sys-GMM *LPI*	IV *mcs*	Sys-GMM *mcs*
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Anderson LM (p-val)	0.000	—	0.000	—	0.000	—	0.000	—
Sargan/Hansen (p-val)	0.543	0.591	—	0.669	—	0.545	—	0.409
AR(1) (p-val)	—	0.001	—	0.001	—	0.001	—	0.001
AR(2) (p-val)	—	0.178	—	0.512	—	0.170	—	0.120
Instruments	L2_edug, L3_edug	L2–L3.edug	PCOM_Index	L2–L3.ae	PCOM_Index	L2–L3.LPI	PCOM_Index	L2–L3.mcs

Notes: *Dependent variable: per capita GDP growth (gdpgp). All specifications include country fixed effects and a lagged dependent variable. Standard errors in parentheses. IV specifications estimated via xtivreg2 (FE). System GMM estimated via xtabond2 (two-step, Windmeijer-corrected robust standard errors, collapsed instruments). ae = access to electricity. *** p < 0.01, ** p < 0.05, * p < 0.10.*

IV/2SLS and System GMM Robustness — Sub-Saharan Africa Panel

All IV diagnostics pass cleanly — Cragg-Donald F-statistics range from 33 to 1,620, all comfortably above the Stock-Yogo 10% critical value of 16.38, and Anderson LM statistics reject underidentification at the 1% level in all columns. The lagged dependent variable is positive and significant across all eight specifications (0.127–0.327, $p < 0.01$), confirming dynamic persistence. Once endogeneity is corrected, education expenditure (IV: 0.286, $p < 0.10$) confirms a marginally positive growth effect; the System GMM lagged coefficient is positive but insignificant, suggesting a contemporaneous rather than persistent channel. Access to electricity (IV: 0.282, $p < 0.01$; Cragg-Donald F = 33.4) delivers a robust positive effect, confirmed by System GMM. Logistics performance (IV: 14.918, $p < 0.01$; Cragg-Donald F = 111.609) registers the largest growth coefficient in the study once instrumented — substantial infrastructure quality improvement generates large returns in SSA. ICT infrastructure (IV: 0.022, $p < 0.01$; Cragg-Donald F = 726.240) is consistently confirmed as a positive growth driver. Capital formation is positive and significant across all eight specifications, and government consumption is consistently negative. All GMM specifications satisfy AR(2) and Hansen/Sargan p-values confirm instrument exogeneity. Endogeneity correction consistently strengthens the core findings, with infrastructure proxies individually generating growth dividends in SSA; the null result on complementarity terms is therefore not attributable to endogeneity bias.

5. Conclusion

This study investigates the long-run relationship between infrastructure, education spending, and economic growth across Sub-Saharan Africa, Asia, and Latin America. Rather than confirming a general complementarity hypothesis, the findings make a more precise empirical statement: education expenditure does not activate complementarity with infrastructure in the long run across any of the three regions examined. Where interaction effects are detectable, they reflect absorptive capacity failure — higher spending attenuates, rather than amplifies, the growth contribution of digital infrastructure in environments where institutional instability prevents expenditure from building effective human capital. This null-and-attenuation result is a substantive finding, not a null result to be apologised for. It reframes the policy question from how much to co-invest to what conditions must first be met for co-investment to generate growth. Using a heterogeneous dynamic panel framework, the analysis distinguishes short-run adjustment dynamics from long-run equilibrium relationships, allowing for regional heterogeneity and convergence behaviour.

Across all three regions, the results highlight the central role of **physical capital accumulation** and structural growth fundamentals in driving long-run per capita GDP growth. Gross fixed capital formation consistently emerges as a strong and positive determinant of growth, while government expenditure exhibits mixed or negative effects, reflecting potential inefficiencies or crowding-out of private investment. Conditional convergence is evident across regions, as lower-income economies grow faster than higher-income counterparts, emphasizing the persistent relevance of catch-up dynamics.

Region-specific insights reveal important contrasts:

1. In **Asia**, infrastructure expansion and education spending show limited direct or interactive effects on long-run growth, suggesting that the null complementarity result reflects the absorptive capacity interpretation developed in Section 2.4: spending preconditions are substantially in place in More Stable economies, and marginal returns to additional education or infrastructure expenditure are consequently low. For Less Stable economies, the divergence of convergence dynamics confirms that stabilisation and institutional reform must precede large-scale co-investment for growth dividends to materialise.
2. In **Latin America**, physical capital and digital connectivity (mobile penetration) are significant drivers, whereas traditional infrastructure measures and education spending exert limited direct or complementary effects. Sub-sample analysis reveals that in less stable economies, mobile connectivity is particularly important, highlighting the role of ICT in mitigating structural constraints, whereas complementarities between education and infrastructure remain weak overall.
3. In **Sub-Saharan Africa**, infrastructure and education complementarity appears more context-dependent. Mobile connectivity and gross fixed capital formation positively influence growth, while government expenditure and certain infrastructure measures dampen growth. Interaction terms between education and infrastructure are largely insignificant, with the exception of a negative and significant edug×mcs — an absorptive capacity attenuation effect rather than positive synergy. This finding underscores that the binding constraint in SSA is not the scale of co-investment but the quality of human

capital and institutional conditions needed to convert infrastructure expansion into productivity gains. Robustness checks confirm that these findings are stable across alternative model specifications, including the exclusion of broad money and terms-of-trade controls.

4. Several limitations of this study warrant acknowledgement. First, the primary education proxy — public expenditure as a percentage of GDP — measures fiscal inputs rather than quality outcomes. Quality-adjusted human capital measures, such as cognitive test scores, consistently generate stronger growth associations than spending levels (Hanushek and Woessmann, 2008), and the null and negative interaction results reported here are best interpreted as reflecting the failure of spending to build effective human capital rather than a genuine null effect of education on growth itself. Data availability constrains the use of quality-adjusted measures across the full panel period, and future research employing harmonised learning outcome measures would sharpen the absorptive capacity interpretation. Second, the LPI is available only from 2007, creating an unbalanced time dimension in the logistics channel and limiting inference on long-run logistics effects. Third, the stability-regime sub-samples are constructed from long-run averages of inflation and macroeconomic stability indicators; richer institutional measures or time-varying regime classifications would allow more precise identification of the threshold conditions under which complementarity emerges.

Policy Implications:

1. Co-investment in infrastructure and education is not sufficient on its own: the empirical results show that education expenditure does not independently activate complementarity with any infrastructure type across the three regions examined. Policymakers should therefore prioritise improving the quality and institutional effectiveness of education delivery — rather than simply increasing spending — before expecting co-investment to generate growth dividends. The negative and significant edug×mcs interaction in SSA and less stable Latin American economies confirms that absorptive capacity is the binding constraint.
2. Private capital formation remains vital; public expenditure should be targeted toward efficiency-enhancing projects rather than broadly expansionary fiscal spending.
3. Stabilisation and institutional quality must precede large-scale infrastructure and education co-investment in less stable economies. The reversal of convergence dynamics in Asian less stable economies — where higher initial income predicts faster growth rather than catch-up — confirms that macroeconomic instability can permanently redirect an economy onto a divergent growth path. For SSA and Latin America's less stable economies, stabilisation is not a complement to investment policy; it is a precondition for it.
4. Digital infrastructure investment offers the clearest and most consistent growth dividend in SSA and Latin America: mcs coefficients of 0.031 and 0.027 respectively are among the most robustly identified results in the study, stable across estimators and specifications. Expanding mobile connectivity in these regions should be a near-term policy priority, distinct from and sequenced ahead of broader education–infrastructure co-investment frameworks whose effectiveness depends on longer-run institutional development.

In conclusion, this study's contribution to development economics is evidence that **the growth impact of infrastructure and education spending depends on regional context and, more fundamentally, on whether the conditions exist for that spending to build effective human capital**, so that complementarity is conditional on absorptive capacity rather than a universal feature of co-investment. This qualifies a coordination logic that runs through much of development policy: stabilisation, institutional quality, and human capital effectiveness are not complements to infrastructure–education co-investment but preconditions for it. For multilateral lenders and national planning agencies, the practical implication is sequencing — building institutional and human-capital foundations ahead of, rather than alongside, large-scale co-investment programmes — since spending coordination alone does not unlock the growth potential these programmes assume. The paper's advance over prior single-country and single-mechanism studies is twofold: it is, to the author's knowledge, the first to test infrastructure–education complementarity within a common dynamic error-correction framework simultaneously across Sub-Saharan Africa, Asia, and Latin America, and it grounds the resulting null and negative interaction effects in a specific, evidence-based channel — administrative leakage and service-delivery failure documented in the public expenditure tracking and teacher absenteeism literature — rather than leaving "absorptive capacity" as an unexplained residual label. Future work using expenditure tracking or classroom-level delivery data directly, rather than the budgeted-spending proxy used here, would allow this channel to be tested more precisely than the present cross-regional comparison permits.

Declarations

Conflict of Interest:

The author declares no conflict of interest.

AI Use Statement:

AI assistance (Claude, Anthropic) was used in editing and formatting this manuscript for journal submission. All intellectual content, empirical analysis, data, results, and interpretations are entirely the author's own work.

Funding:

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability:

Replication data and Stata code are publicly available at Zenodo: https://doi.org/10.5281/zenodo.20099701

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