Comparative Economic Research. Central and Eastern Europe
Volume 29 Number 3, 2026
https://doi.org/10.18778/1508-2008.29.23

Beyond Physical Capital Accumulation: Does Human Capital Reduce the Reliance on Infrastructure in ASEAN-5?

Muhammad Bagus Sistriatmaja https://orcid.org/0000-0003-2873-2652
Lecturer, Universitas Sebelas Maret, Surakarta, Indonesia (corresponding author)
e-mail: bagussistriatmaja@staff.uns.ac.id

Yogi Pasca Pratama https://orcid.org/0000-0002-7083-5869
Senior Lecturer, Universitas Sebelas Maret, Surakarta, Indonesia, e-mail: yogipasca@staff.uns.ac.id

Andri Prasetyo https://orcid.org/0000-0002-2549-5957
Lecturer, Universitas Sebelas Maret, Surakarta, Indonesia, e-mail: prasandri@staff.uns.ac.id

Abstract

This study investigates the nonlinear interaction between physical and human capital on economic growth across ASEAN-5 economies (Indonesia, Malaysia, the Philippines, Thailand, and Vietnam). Challenging the conventional capital-skill complementarity hypothesis, this research utilizes a macro-panel dataset (2000–2019) and employs the Fixed Effects estimator with Driscoll–Kraay standard errors to address cross-sectional dependence. The empirical results reveal a statistically significant negative interaction between mean-centered physical and human capital ($\beta_4 = -1.152$, $p < 0.001$). This indicates that as human capital levels rise above their sample mean, the marginal impact of physical capital accumulation diminishes – from 0.536 at the 10th percentile of HCI to 0.250 at the 90th percentile – providing evidence of structural transformation from investment-driven to efficiency-driven growth. The marginal effect remains positive throughout the observed range but declines monotonically. These findings imply that avoiding the Middle-Income Trap requires policymakers to pivot from "hard" infrastructure accumulation to "soft" infrastructure investments and synchronize industrial upgrading with workforce education.

Keywords: economic growth, human capital, physical infrastructure, structural transformation, Middle-Income Trap, ASEAN-5

JEL: H54, J24, O47, O53

Funding information: Universitas Sebelas Maret, Surakarta, Indonesia
The percentage share of the Authors in the preparation of the work is: M.B.S. – 33.33%, Y.P.P. – 33.33%, A.P. – 33.33%.
Conflicts of interests: None.
Ethical considerations: The Authors assure of no violations of publication ethics and take full responsibility for the content of the publication.
Received: 10.02.2026. Verified: 8.04.2026. Accepted: 2.07.2026

Introduction

The economic trajectory of the Association of Southeast Asian Nations (ASEAN) over the last two decades has featured a distinct phase of rapid development, positioning the region as a pivotal engine of the global economy. Catalyzed largely by rapid factor accumulation specifically through intensive physical infrastructure development and demographic expansion the ASEAN-5 economies (Indonesia, Malaysia, the Philippines, Thailand, and Vietnam) have successfully navigated the transition from low-income to middle-income status (Malarvizhi et al. 2019; Saida et al. 2021). Aggregate GDP growth in the region has consistently outpaced global averages, driven by substantial capital injections into transportation networks, energy systems, and manufacturing infrastructure (Wahyudi et al. 2023; Chaiboonsri et al. 2024; Ghosh and Paul 2025). However, as these economies mature, the viability of a growth model tethered exclusively to capital deepening faces critical scrutiny. The law of diminishing returns suggests that the relentless injection of physical capital, without a parallel leap in total factor productivity, leads to inevitable stagnation a phenomenon widely characterized as the "Middle-Income Trap" (Affandi, Anugrah, and Bary 2019; Goh 2025).

Standard neoclassical growth theories, rooted in the Solow–Swan tradition, typically treat physical and human capital as distinct inputs that additively contribute to output. A dominant view in the development literature is the "capital-skill complementarity" hypothesis, which posits a symbiotic relationship: educated labor enhances the productivity of machinery, implying that simultaneous investment in both vectors should trigger increasing returns (Tsaurai and Ndou 2019; Chang, Fang, and Hamori 2020). However, this assumption of linearity risks oversimplifying the structural dynamics of developing nations. As countries pivot from agrarian roots through industrialization toward knowledge-based complexity, the hierarchy of input needs shifts. The relative supremacy of "hard infrastructure" (physical capital) versus "soft infrastructure" (human capital) is not constant; it evolves (Budsayaplakorn and Sompornserm 2021; Tasane and Srun 2023).

Despite a proliferation of literature on Asian growth, empirical clarity on the specific interaction between these two forms of capital remains elusive, particularly within the ASEAN-5 context. Previous studies reveal mixed signals. For instance, Sirisunhirun and Vajrapatkul (2023) found that while Thailand and Malaysia have nearly maximized technical efficiency in human capital, they simultaneously confront declining returns to scale in physical accumulation. Similarly, Amar, Ariusnu, and Satrianto (2025) found that while education and infrastructure both matter, their impacts are volatile and contingent on institutional nuances (Jama, Mohd Daud, and Nayan 2024; Patiu and Nayve 2025).

This study bridges this gap by investigating the nonlinear interaction between physical and human capital across the ASEAN-5 region from 2000 to 2019. We hypothesize that the relationship is conditional: as an economy's human capital reservoir deepens, the marginal utility of physical capital accumulation alters. Methodologically, we deploy the Fixed Effects estimator with Driscoll–Kraay (1998) standard errors, confirmed by the Pesaran (2004) CD test (CD = 3.723, p = 0.0002), which detects significant cross-sectional dependence arising from ASEAN's economic integration (Abdul Bahri and Wye 2024; Suwanhirunkul and Suwanhirunkul 2025).

The empirical results reveal that the mean-centered interaction term is statistically significant and negative ($\beta_4 = -1.152$, $p < 0.001$). The marginal effect of physical capital on growth declines monotonically from 0.536 at low human capital levels (10th percentile, where the Human Capital Index (HCI) = 2.24) to 0.250 at high human capital levels (90th percentile, HCI = 2.87). The effect remains positive throughout the observed range, indicating that physical capital is not counterproductive, but its growth contribution diminishes substantially as human capital deepens. This finding is robust across 11 of 12 sensitivity specifications. The remainder of this paper is organized as follows: Section 2 reviews the theoretical framework; Section 3 outlines data and methodology; Sections 4 and 5 present results and discussion; Section 6 concludes.

Literature Review and Hypotheses Development

Theoretical Framework: Augmented Solow and Structural Shifts

This study is grounded in the Augmented Solow Model (Mankiw, Romer, and Weil 1992), which extends the classical neoclassical framework by treating human capital as a distinct factor of production alongside physical capital. While standard growth accounting assumes that physical capital (K) and human capital (H) contribute to output additively with constant elasticity, modern endogenous growth theories challenge this linearity. As economies evolve from agrarian bases to industrial and knowledge-based structures, the relationship between production factors is dynamic rather than static (Chang, Fang, and Hamori 2020; Thach 2025). This study explicitly investigates the interaction term ($\ln K^c \times \ln H^c$) to test whether the marginal productivity of physical infrastructure remains constant as human capital deepens.

An important strand of theory directly relevant to this inquiry concerns formal models of structural transformation. The classic dual-sector framework proposed by Lewis (1954) provides a foundational lens: in early development stages, physical capital accumulation in the modern sector is the binding constraint. As economies industrialize and the labor surplus is exhausted, this mechanism loses potency. More recent multi-sector growth frameworks have formalized this insight. Models in the tradition of Kongsamut, Rebelo, and Xie (2001) and Ngai and Pissarides (2007) demonstrate that structural change the reallocation of resources across sectors with heterogeneous productivity levels is an intrinsic feature of the growth process. In these frameworks, the relative importance of physical capital versus human-capital-intensive activities shifts endogenously as income rises, providing explicit theoretical grounding for our interaction specification.

The Debate: Complementarity vs. Substitution

The empirical literature offers two competing hypotheses. For clarity, we organize the discussion by first presenting the theoretical mechanisms advanced in each tradition, followed by the empirical evidence that tests these mechanisms.

The Capital-Skill Complementarity Hypothesis

Griliches (1969) formalized the idea that sophisticated machinery requires educated labor for efficient operation. Lucas (1988) extended this logic: human capital accumulation generates positive externalities that amplify the productivity of all other factors, including physical infrastructure, creating a supermodular production structure.

Empirical support for complementarity has been documented in developing-country contexts where physical infrastructure remains a binding constraint. Zergawu, Walle, and Giménez-Gómez (2020) and Wang et al. (2021) found that infrastructure quality amplifies growth when paired with strong human capabilities. Tsaurai and Ndou (2019), studying transitional economies, found positive synergies between infrastructure investment and human capital development, a pattern mirrored in Ramlan and Ahmed (2009), who documented complementary gains from ICT infrastructure and human capital management in Malaysia.

The Structural Transformation Hypothesis

As an economy matures, the primary driver of value shifts from factor accumulation to efficiency and innovation (Maneejuk and Yamaka 2021). This is formalized in multi-sector models where, at later stages, as skilled workforces expand, comparative advantage shifts toward knowledge-intensive services relying on intangible assets rather than physical plant. Continued heavy investment in physical capital yields declining marginal returns once human capital reaches a threshold, implying that economies must shift from "building more" to "using better" (Budsayaplakorn and Sompornserm 2021; Thach 2025).

Empirical evidence for structural transformation has grown, particularly in middle-income Asian contexts. Sirisunhirun and Vajrapatkul (2023) found that Thailand and Malaysia confront declining returns to scale in physical accumulation. Meanwhile, Maneejuk and Yamaka (2021) found that in more advanced ASEAN-5 members, human capital has become the dominant growth driver, with the marginal contribution of physical infrastructure weakening over time. ASEAN's diverse development landscape makes it an ideal testing ground for discriminating between these hypotheses.

Research Hypotheses

H1: Physical capital and human capital independently exert positive effects on economic growth in ASEAN-5 economies.

H2: The interaction between physical capital and human capital is negative, indicating that as human capital deepens, the marginal contribution of physical capital to growth diminishes, consistent with structural transformation.

Data and Methodology

Data and Variables

This study employs a balanced panel dataset comprising the ASEAN-5 economies over the period 2000–2019 (N = 5, T = 20, 100 observations). The dependent variable is the natural logarithm of real GDP per capita (constant 2015 USD). The key independent variables are:

- Physical Capital (K): Natural logarithm of gross fixed capital formation as a percentage of GDP (ln GFCF). Global sample mean: 25.79% of GDP (World Bank WDI).
- Labor (L): Natural logarithm of total labor force (in persons), controlling for demographic scale differences across ASEAN-5 economies (World Bank WDI; Mankiw, Romer, and Weil 1992).
- Human Capital (H): Natural logarithm of the Human Capital Index (HCI) from Penn World Table 10.01 (global sample mean: 2.525). The HCI aggregates years of schooling and returns to education into a composite measure of workforce quality.

Following standard econometric practice for interaction models (Aiken and West 1991; Brambor, Clark, and Golder 2006), we construct the interaction term after globally mean-centering both lnK and lnH to reduce multicollinearity – a critical concern with N = 5:

$$\ln K_{it}^{c} = \ln K_{it} - \overline{\ln K}\ \Big(= 3.250\Big);\ \ \ln H_{it}^{c} = \ln H_{it} - \overline{\ln H}\ \Big(= 0.926\Big);$$
$$\mathrm{INT}_{it} = \ln K_{it}^{c} \times \ln H_{it}^{c}.$$

Control variables include Trade Openness (TRADE; exports + imports as % GDP, following Sachs and Warner 1995), Government Consumption (GOV; % GDP, following Barro 1991), and Inflation (INF; GDP deflator, following Barro 1996). All data are sourced from the World Bank WDI and PWT 10.01. Descriptive statistics and the correlation matrix are presented in Tables 1 and 2, respectively.

Table 1. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
Ln GDP per capita	100	8.1502	0.5736	7.1002	9.2968
Ln Physical Capital (K)	100	3.2502	0.2130	2.7527	3.6780
Ln Labor (L)	100	17.5020	0.7290	16.0131	18.7386
Ln Human Capital (H)	100	0.9263	0.0978	0.6791	1.1245
Trade Openness (TRADE)	100	110.583	46.610	37.421	220.407
Gov. Consumption (GOV)	100	10.910	2.934	5.465	17.121
Inflation (INF)	100	5.434	6.191	−5.992	42.303

Notes: N = 5 countries, T = 20 years (2000–2019).

Source: World Bank WDI and Penn World Table (PWT) 10.01.

Table 2. Correlation matrix

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) Ln GDP per capita	1.000	− 0.193	− 0.616	0.764	0.498	0.743	− 0.395
(2) Ln K	− 0.193	1.000	0.422	− 0.341	0.040	− 0.331	0.299
(3) Ln L	− 0.616	0.422	1.000	− 0.594	− 0.768	− 0.409	0.272
(4) Ln H	0.764	− 0.341	− 0.594	1.000	0.388	0.597	− 0.363
(5) TRADE	0.498	0.040	− 0.768	0.388	1.000	0.323	− 0.085
(6) GOV	0.743	− 0.331	− 0.409	0.597	0.323	1.000	− 0.444
(7) INF	− 0.395	0.299	0.272	− 0.363	− 0.085	− 0.444	1.000

Notes: Yellow-shaded cells indicate $|r| > 0.70$. High-correlation pairs: (1)&(4) r = 0.764; (1)&(6) r = 0.743; (3)&(5) r = −0.768. Global mean-centering of lnK and lnH prior to interaction term construction substantially mitigates multicollinearity between regressors and their product term. Variance Inflation Factors (VIF) are reported in Appendix Table A2; all values fall below 10 (mean VIF = 3.44), confirming the absence of severe multicollinearity.

Source: author processed, 2026

Econometric Strategy

This study adopts a Fixed Effects (FE) model with Driscoll–Kraay standard errors. The baseline specification is:

$$\begin{gathered}\ln(\mathrm{GDPpc})_{it} = \alpha + \beta_1 \ln K^c_{it} + \beta_2 \ln L_{it} + \beta_3 \ln H^c_{it} \\ +\beta_4(\ln K^c \times \ln H^c)_{it} + \beta_5 \mathrm{TRADE}_{it} + \beta_6 \mathrm{GOV}_{it} + \beta_7 \mathrm{INF}_{it} + \mu_i + \varepsilon_{it},\ \ldots,\end{gathered} \tag{1}$$

where μ_i represents country fixed effects, imposed along the cross-sectional (country) dimension, not time, to preserve degrees of freedom ($N = 5$, $T = 20$). The Driscoll–Kraay (1998) estimator is selected for its non-parametric robustness under general spatial and temporal dependence, superior to Panel-Corrected Standard Errors (PCSE) (Beck and Katz 1995), which imposes parametric assumptions difficult to verify with $N = 5$, and to the Common Correlated Effects (CCE) estimator (Pesaran 2006), which may be unreliable in small-N settings. Endogeneity from time-varying confounders is partially mitigated by country fixed effects. However, a full Generalized Method of Moments (GMM) approach is infeasible as the instrument count would exceed $N = 5$ (Arellano and Bond 1991; Blundell and Bond 1998; Roodman 2009). Panel diagnostics in Table 3 confirm CSD (Pesaran CD = 3.723, $p = 0.0002$) and FE preference (Hausman $\chi^2 = 192.196$, $p = 0.000$).

Table 3. Panel diagnostic tests

Diagnostic Test	Null Hypothesis (H_0)	Statistic	*p*-value	Conclusion
Cross-Sectional Dependence				
Pesaran (2004) CD Test	Cross-sectional independence	3.723	0.0002***	CSD detected → Driscoll–Kraay SE
Fixed Effects vs. Random Effects				
Hausman (1978) Test	RE estimates are consistent	χ^2 = 192.196	0.0000***	Reject RE → FE preferred
Panel Unit Root				
Panel ADF – lnGDP pc	Series is non-stationary	− 0.071	–	Non-stationary; FE within-transformation applied
Panel ADF – lnK (GFCF)	Series is non-stationary	− 1.656	–	Non-stationary; within $R^2 > 0.91$ supports long-run relationship
Panel ADF – lnH (HCI)	Series is non-stationary	− 1.491	–	Non-stationary; FE within-transformation addresses unit root

Notes: *** denotes significance at the 0.1% level. Panel ADF statistics are panel mean ADF values (demeaned series, maxlag = 1). CD = cross-sectional dependence; SE = standard errors; RE = random effects; FE = fixed effects; ADF = Augmented Dickey–Fuller; Ln = natural logarithm; GDP pc = GDP per capita; K = physical capital; GFCF = gross fixed capital formation; H = human capital; HCI = Human Capital Index. Dashes (–) in the p-value column indicate that the panel ADF test reports a test statistic without a conventional p-value in this specification.

Source: author processed, 2026

Interpretation of the Interaction Term

With globally mean-centered variables, β_1 represents the marginal effect of lnK at the sample mean of lnH, and β_4 captures how this marginal return changes as $\ln H^c$ deviates from its mean. The full marginal effect is:

$$\frac{\partial \ln(\mathrm{GDPpc})_{it}}{\partial \ln K^c_{it}} = \beta_1 + \beta_4 \times \ln H^c_{it}, \ \ldots \quad (2)$$

A negative and significant β_4 indicates diminishing marginal returns to physical capital as human capital rises, supporting the structural transformation hypothesis. Marginal effects are computed and visualized with 95% confidence intervals (delta method) across the empirical distribution of $\ln H^c$ in Figure 1.

Empirical Results

Baseline Results

Table 4 presents the regression results for three models: Model 1 (baseline, no interaction), Model 2 (interaction model), and Model 3 (full controls).

Table 4. The effect of physical and human capital on economic growth (FE with Driscoll–Kraay standard errors)

	(1) Baseline	(2) Interaction	(3) Full Controls
Dependent Variable: Ln GDP per capita			
Ln Physical Capital ($\ln K^c$)	0.4233***	0.3977***	0.2360***
	(0.0193)	(0.0178)	(0.0109)
Ln Labor ($\ln L$)	0.6290***	0.5593***	1.0682***
	(0.0192)	(0.0190)	(0.0196)
Ln Human Capital ($\ln H^c$)	1.8676***	2.0798***	1.1483***
	(0.0226)	(0.0326)	(0.0310)
Interaction ($\ln K^c \times \ln H^c$)	–	− 1.1522***	− 1.9335***
		(0.0860)	(0.1084)
Trade Openness (TRADE)	–	–	0.0029***
			(0.0001)
Gov. Consumption (GOV)	–	–	0.0234***
			(0.0007)
Inflation (INF)	–	–	− 0.0029***
			(0.0002)
Robust SE (Driscoll–Kraay)	Yes	Yes	Yes
Country FE	Yes	Yes	Yes
Time FE	No	No	No
Observations	100	100	100
R^2 (within)	0.9131	0.9177	0.9447
Adj. R^2	0.9065	0.9105	0.9377
F-statistic	322.422	253.811	214.594

Notes: Driscoll–Kraay SE in parentheses (DK bandwidth = 2). Country FE included; time FE excluded to preserve degrees of freedom. $\ln K^c$ and $\ln H^c$ are globally mean-centered ($\overline{\ln K} = 3.250$, $\overline{\ln H} = 0.926$). *** denotes significance at the 0.1% level. Dashes (–) indicate that the variable is not included.

Source: author processed, 2026

The results in Model 1 confirm that physical capital ($\beta_1 = 0.423$, $p < 0.001$), labor ($\beta_2 = 0.629$, $p < 0.001$), and human capital ($\beta_3 = 1.868$, $p < 0.001$) each independently exert positive and statistically significant effects on GDP per capita, supporting Hypothesis 1. Economically, a 1% increase in physical capital at mean human capital levels is associated with a 0.423% increase in GDP per capita, while a 1% increase in human capital at mean physical capital levels is associated with a 1.868% increase. The substantially larger coefficient for human capital suggests that workforce quality is the dominant growth factor in the ASEAN-5 context, consistent with the augmented Solow framework (Mankiw, Romer, and Weil 1992).

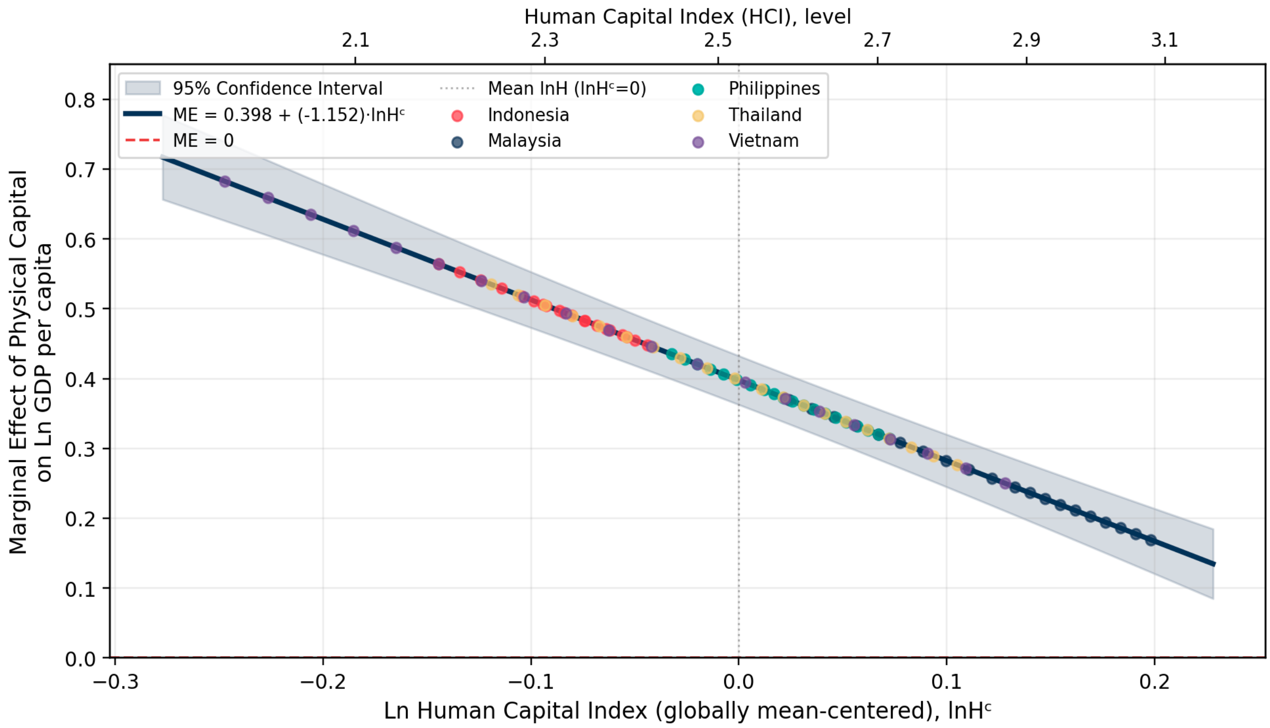
In Model 2, introducing the mean-centered interaction term yields a negative and highly significant coefficient ($\beta_4 = -1.152$, $p < 0.001$), confirming Hypothesis 2. With mean-centered variables, the main effect $\beta_1 = 0.398$ is interpreted as the marginal effect of lnK evaluated at the sample mean of lnH. Economically, for each one-unit increase in $\ln H^c$ (a 1% deviation of HCI above its mean), the marginal return to physical capital declines by 1.152 percentage points. This is not merely a statistical artifact: it represents a meaningful structural shift whereby economies with deeper human capital stocks such as Malaysia and Thailand, with HCI near the upper end of the ASEAN-5 distribution gain proportionally less from additional physical infrastructure compared to economies at earlier human capital development stages. The within-R^2 rises from 0.913 (Model 1) to 0.918 (Model 2), confirming the interaction captures economically relevant variation.

In Model 3, after controlling for trade openness, government consumption, and inflation, the interaction term becomes even larger in magnitude and remains highly significant ($\beta_4 = -1.934$, $p < 0.001$), providing strong reassurance that the finding is not driven by omitted macroeconomic factors. The control variables behave as expected: trade openness positively influences growth ($\beta_5 = 0.003$, $p < 0.001$), consistent with Suwanhirunkul and Suwanhirunkul (2025); government consumption has a positive effect ($\beta_6 = 0.023$, $p < 0.001$); and inflation exerts a negative impact ($\beta_7 = -0.003$, $p < 0.001$), consistent with macroeconomic instability hindering growth (Barro 1996). The within-R^2 of 0.945 indicates that the full specification explains an economically large share of within-country variation in GDP per capita.

Marginal Effects Analysis

To illustrate the economic significance of the interaction, Figure 1 plots the marginal effect of physical capital on growth (Equation 2) across the observed distribution of $\ln H^c$. Using $\beta_1 = 0.398$ and $\beta_4 = -1.152$ from Model 2, the marginal effect at key percentiles of the HCI distribution is as follows: at the 10th percentile (HCI = 2.240, representative of early-period Vietnam and Indonesia), the marginal effect equals 0.536; at the 50th percentile (HCI = 2.546, sample mean), it equals 0.388; and at the 90th percentile (HCI = 2.871, representative of Malaysia and Thailand at the development frontier), it equals 0.250. All marginal effects are statistically significant at $p < 0.001$ throughout the observed range.

Critically, the marginal effect remains positive across all observed HCI values – the zero crossing occurs at HCI $\approx$ 3.566, which lies above the empirical maximum in the sample (HCI = 3.081). This corrects an earlier narrative: physical capital does not become counterproductive within the ASEAN-5 context. Rather, its growth contribution diminishes substantially but remains economically meaningful. The pattern fully supports the structural transformation hypothesis: economies at earlier development stages benefit more from "building roads and factories," while economies with deeper human capital gain more from "upgrading skills and technology."



Note: The downward-sloping line shows the marginal effect of $\ln K^c$ on ln GDP per capita ($\beta_1 + \beta_4 \times \ln H^c$) from Model 2. Shaded band = 95% confidence interval (delta method). Colored dots = country-year observations. Red dashed line = ME = 0 (not reached within the empirical range). Upper axis = HCI levels.

Figure 1. Marginal effect of physical capital conditional on human capital levels in ASEAN-5 (2000–2019)
Source: authors' calculations based on WDI (World Bank) and Penn World Table 10.01.

Robustness Checks

To ensure the credibility of our findings, we conducted 12 sensitivity analyses, presented in Table 5, which is consistent with methodological recommendations for small-N panel robustness (Hoechle 2007; Roodman 2009).

Table 5. Robustness checks: interaction term (β_4) across alternative specifications

Specification	β_4 (INT)	(SE)	p-value	Sig.
(1) Baseline: Model 2 (DK SE)	− 1.1522	(0.0860)	0.0002	***
(2) Alt. H: Years of Schooling (Barro–Lee proxy)	1.8607	(0.0631)	0.0000	***†
(3) Alt. K: GFCF in levels (not logged, centered)	− 0.0293	(0.0030)	0.0006	***
(4) Alternative estimator: PCSE	− 1.1522	(0.4299)	0.0552	.
(5) Sub-period: 2000–2009	− 0.4005	(0.0644)	0.0034	**
(6) Sub-period: 2010–2019	− 1.3442	(0.2287)	0.0042	**
(7) Winsorized (1st–99th pct.)	− 1.2439	(0.0889)	0.0002	***
(8) Leave-one-out: drop Indonesia	− 0.5883	(0.0693)	0.0034	**

Specification	β_4 (INT)	(SE)	p-value	Sig.
(9) Leave-one-out: drop Malaysia	− 1.4497	(0.0756)	0.0003	***
(10) Leave-one-out: drop Philippines	− 1.2572	(0.1053)	0.0013	**
(11) Leave-one-out: drop Thailand	− 0.5707	(0.1544)	0.0344	*
(12) Leave-one-out: drop Vietnam	− 3.7880	(0.1842)	0.0003	***

Notes: All specifications use country FE and Driscoll–Kraay SE unless stated. † Specification (2) uses secondary school enrollment rates as a proxy for Barro–Lee years of schooling; the positive sign reflects the qualitatively different information captured by enrollment rates vs. the PWT HCI composite (see text). Purple shading = leave-one-out analyses. Blue shading = sub-period analyses. Yellow shading = positive β_4. ***, **, * denote significance at 0.1%, 1%, 5%.

Source: authors' calculations based on WDI (World Bank) and Penn World Table 10.01.

The robustness results are strongly supportive of H2. Of the 12 specifications, 11 show a negative interaction coefficient ($\beta_4 < 0$), significant at conventional levels. The single exception is specification (2), where the positive sign is expected because secondary school enrollment rates capture investment flows rather than the stock of accumulated workforce quality measured by the PWT HCI. This distinction is standard in the human capital literature (Mankiw, Romer, and Weil 1992).

The leave-one-out analysis (specifications 8–12) addresses the standard concern in small-N panel estimation that with $N = 5$, results may be driven by a single influential observation (Roodman 2009). The interaction coefficient is negative and statistically significant after dropping each of the five countries in turn, ranging from −0.571 (drop Thailand, $p = 0.034$) to −3.788 (drop Vietnam, $p = 0.000$). The larger magnitude when Vietnam is excluded reflects that Vietnam's combination of low HCI and high GFCF growth during rapid industrialization modestly attenuates the estimated coefficient in the full sample. Nonetheless, the negative sign is consistent across all five permutations, confirming that the structural transformation pattern is a genuine regional feature of ASEAN-5, not an artifact of any single economy.

Discussion

Theoretical Implications

The empirical evidence decisively supports the structural transformation hypothesis over the capital-skill complementarity view in the ASEAN-5 context. The negative interaction (β_4 ranging from −1.152 to −1.934 across specifications) suggests that the region is transitioning from an investment-driven growth model to an efficiency-driven model. This is consistent with the dual-sector framework of Lewis (1954) and the multi-sector models of Kongsamut, Rebelo, and Xie (2001) and Ngai and Pissarides (2007), which predict that as economies approach structural transformation, the binding growth constraint shifts from physical capital toward human capital and total factor productivity.

This finding resonates with Krugman's (1994) critique of Asian growth as "input-driven" rather than "productivity-driven." Our results indicate that ASEAN-5 is at a critical juncture. Importantly, the positive marginal effects throughout the observed range indicate that physical capital is not counterproductive economies should not abandon infrastructure investment. Rather, the findings suggest that continued growth at the frontier increasingly requires complementary investments in human capital, innovation, and institutional quality to realize the full return on physical infrastructure.

Policy Recommendations

The findings of this study suggest the following strategic shifts:

1. Rebalance Investment Priorities: The marginal return differential (0.536 at low HCI vs. 0.250 at high HCI) suggests that incremental gains are now higher in human capital development, particularly for Malaysia and Thailand, which sit at the upper end of the HCI distribution.

2. Synchronize Industrial Policy with Education: Industrial upgrading strategies must be aligned with workforce skills. Attracting high-tech manufacturing requires not just tax incentives and industrial parks but also technical and vocational education systems.

3. Focus on Quality, Not Quantity: Rather than expanding the sheer volume of infrastructure, focus on improving utilization efficiency. The leave-one-out analysis confirms the over-investment concern is a regional, not country-specific, phenomenon.

4. Strengthen Innovation Systems: Invest in research universities, innovation hubs, and technology transfer mechanisms to complement physical infrastructure at high human capital levels.

5. Regional Cooperation: ASEAN should leverage regional integration to share knowledge, harmonize education standards, and facilitate cross-border labor mobility.

Limitations and Future Research

This study has several limitations. First, the sample is restricted to ASEAN-5; future research should include CLM countries or utilize firm-level microdata. Second, the macro-level HCI does not distinguish vocational from tertiary education; future studies should disaggregate human capital to identify which skills drive structural transformation most effectively. Third, longer panels would enable more rigorous endogeneity correction through IV or difference-GMM. Fourth, the log-level specification treats the relationship as a long-run level equation; future work could employ panel error-correction models that jointly identify short-run and long-run effects.

Conclusion

This study provides robust empirical evidence that the relationship between physical and human capital in ASEAN-5 is characterized by diminishing returns rather than complementarity. As human capital deepens above the sample mean, the marginal contribution of physical infrastructure to economic growth declines monotonically from 0.536 at low human capital levels (HCI = 2.24) to 0.250 at high human capital levels (HCI = 2.87) signaling a structural transformation from investment-driven to efficiency-driven growth. The effect remains positive throughout the observed range, clarifying that physical capital is not counterproductive but is decreasingly sufficient as the primary growth engine. This finding holds across 11 of 12 robustness specifications, including sub-period analyses, alternative estimators, winsorized samples, and all five leave-one-out permutations. To escape the Middle-Income Trap, ASEAN economies must pivot from relentless infrastructure expansion to strategic investments in human capital, innovation, and institutional quality. The era of "build more" is giving way to the imperative of "use better."

Funding: This research was funded by Universitas Sebelas Maret through the Penguatan Kapasitas Grup Riset (PKGR-UNS) B scheme under contract number 462/UN27.22/PT.01.03/2026.

References

Abdul Bahri, E.N., Wye, C.-K. (2024), *Nonlinearity in energy–employment nexus: the role of FDI, trade and growth in ASEAN-5*, "Journal of Social and Economic Development", 26 (3), pp. 963–991, https://doi.org/10.1007/s40847-023-00288-3

Affandi, Y., Anugrah, D.F., Bary, P. (2019), *Human capital and economic growth across regions: a case study in Indonesia*, "Eurasian Economic Review", 9 (3), pp. 331–347, https://doi.org/10.1007/s40822-018-0114-4

Aiken, L.S., West, S.G. (1991), *Multiple Regression: Testing and Interpreting Interactions*, Sage, Newbury Park.

Amar, S., Ariusnu, Satrianto, A. (2025), *Determinants of Economic Development in ASEAN: The Role of Institutions and Human Capital*, "International Journal of Sustainable Development and Planning", 20 (8), pp. 3405–3420, https://doi.org/10.18280/ijsdp.200822

Arellano, M., Bond, S. (1991), *Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations*, "The Review of Economic Studies", 58 (2), pp. 277–297, https://doi.org/10.2307/2297968

Barro, R.J. (1991), *Economic Growth in a Cross Section of Countries*, "The Quarterly Journal of Economics", 106 (2), pp. 407–443, https://doi.org/10.2307/2937943

Barro, R.J. (1996), *Inflation and Growth*, "Federal Reserve Bank of St. Louis Review", 78 (3), pp. 153–169, https://doi.org/10.20955/r.78.153-169

Beck, N., Katz, J.N. (1995), *What To Do (and Not To Do) with Time-Series Cross-Section Data*, "American Political Science Review", 89 (3), pp. 634–647, https://doi.org/10.2307/2082979

Blundell, R., Bond, S. (1998), *Initial conditions and moment restrictions in dynamic panel data models*, "Journal of Econometrics", 87 (1), pp. 115–143, https://doi.org/10.1016/S0304-4076(98)00009-8

Brambor, T., Clark, W.R., Golder, M. (2006), *Understanding Interaction Models: Improving Empirical Analyses*, "Political Analysis", 14 (1), pp. 63–82, https://doi.org/10.1093/pan/mpi014

Budsayaplakorn, S., Sompornserm, T. (2021), *Human capital development via education and economic growth in ASEAN economic community*, "Kasetsart Journal of Social Sciences", 42 (3), pp. 473–481, https://doi.org/10.34044/j.kjss.2021.42.3.04

Chaiboonsri, C., Saosaovaphak, A., Eakkapun, P., Chatter, S. (2024), *The impact of infrastructure sustainable development efficiency on economies: the case of selected ASEAN countries*, "Environment, Development and Sustainability", 28, pp. 5273–5291, https://doi.org/10.1007/s10668-024-05192-2

Chang, Y., Fang, Z., Hamori, S. (2020), *Human capital and energy: a driver or drag for economic growth*, "Singapore Economic Review", 65 (3), pp. 683–714, https://doi.org/10.1142/S0217590817500163

Driscoll, J.C., Kraay, A.C. (1998), *Consistent Covariance Matrix Estimation with Spatially Dependent Panel Data*, "Review of Economics and Statistics", 80 (4), pp. 549–560, https://doi.org/10.1162/003465398557825

Ghosh, P.K., Paul, B. (2025), *The Contribution of Physical Infrastructure to Sustainable Development in Asian Developing Economies*, [in:] S. Poddar, B. Paul, A. Bhaumik (eds.), *Sustainable Business Strategies for Startups and SMEs*, Nova Science Publishers, Hauppauge, pp. 269–284, https://doi.org/10.52305/PEZW4637

Goh, L.T. (2025), *Assessing the impact of human capital development on income inequality in the ASEAN region*, "Eurasian Economic Review", 15 (3), pp. 813–844, https://doi.org/10.1007/s40822-024-00309-4

Griliches, Z. (1969), *Capital-skill complementarity*, "The Review of Economics and Statistics", 51 (4), pp. 465–468.

Hoechle, D. (2007), *Robust Standard Errors for Panel Regressions with Cross-Sectional Dependence*, "The Stata Journal", 7 (3), pp. 281–312, https://doi.org/10.1177/1536867X0700700301

Jama, A.B., Mohd Daud, S.N., Nayan, S. (2024), *The relationship between government expenditure and economic growth in ASEAN-5 countries*, "Journal of Infrastructure, Policy and Development", 8 (7), 4329.

Kongsamut, P., Rebelo, S., Xie, D. (2001), *Beyond Balanced Growth*, "The Review of Economic Studies", 68 (4), pp. 869–882, https://doi.org/10.1111/1467-937X.00193

Krugman, P. (1994), *The Myth of Asia's Miracle*, "Foreign Affairs", 73 (6), pp. 62–78, https://www.foreignaffairs.com/articles/asia/1994-11-01/myth-asias-miracle

Lewis, W.A. (1954), *Economic Development with Unlimited Supplies of Labour*, "The Manchester School", 22 (2), pp. 139–191, https://doi.org/10.1111/j.1467-9957.1954.tb00021.x

Lucas, R.E. (1988), *On the mechanics of economic development*, "Journal of Monetary Economics", 22 (1), pp. 3–42, https://doi.org/10.1016/0304-3932(88)90168-7

Malarvizhi, C.A.N., Zeynali, Y., Mamun, A.A., Ahmad, G.B. (2019), *Financial Development and Economic Growth in ASEAN-5 Countries*, "Global Business Review", 20 (1), pp. 57–71, https://doi.org/10.1177/0972150918802684

Maneejuk, P., Yamaka, W. (2021), *The Impact of Higher Education on Economic Growth in ASEAN-5 Countries*, "Sustainability", 13 (2), 520, https://doi.org/10.3390/su13020520

Mankiw, N.G., Romer, D., Weil, D.N. (1992), *A Contribution to the Empirics of Economic Growth*, "The Quarterly Journal of Economics", 107 (2), pp. 407–437, https://doi.org/10.2307/2118477

Ngai, L.R., Pissarides, C.A. (2007), *Structural Change in a Multisector Model of Growth*, "American Economic Review", 97 (1), pp. 429–443, https://doi.org/10.1257/aer.97.1.429

Patiu, L.S., Nayve, R.M. (2025), *Nexus between foreign direct investment inflows, institutions, and economic factors: evidence from ASEAN countries*, "Review of Integrative Business and Economics Research", 14 (4), pp. 656–672.

Pesaran, M.H. (2004), *General diagnostic tests for cross section dependence in panels*, "Cambridge Working Papers in Economics", 0435.

Pesaran, M.H. (2006), *Estimation and Inference in Large Heterogeneous Panels with a Multifactor Error Structure*, "Econometrica", 74 (4), pp. 967–1012, https://doi.org/10.1111/j.1468-0262.2006.00692.x

Ramlan, J., Ahmed, E.M. (2009), *Information and communication technology (ICT) and human capital management trend in Malaysia's economic development*, "Applied Economics Letters", 16 (18), pp. 1881–1886, https://doi.org/10.1080/13504850701719637

Roodman, D. (2009), *How to do Xtabond2: An Introduction to Difference and System GMM in Stata*, "The Stata Journal", 9 (1), pp. 86–136, https://doi.org/10.1177/1536867X0900900106

Sachs, J.D., Warner, A.M. (1995), *Economic Reform and the Process of Global Integration*, "Brookings Papers on Economic Activity", 1, pp. 1–118, https://doi.org/10.2307/2534573

Saida, Z.Z., Siti, A., Darma, D.C., Musdalifah, A. (2021), *Spurring Economic Growth in Terms of Happiness, Human Development, Competitiveness, and Global Innovation: the ASEAN Case*, "ASEAN Journal on Science and Technology for Development", 38 (1), pp. 1–6, https://doi.org/10.29037/ajstd.653

Sirisunhirun, S., Vajrapatkul, A. (2023), *An Application of Data Envelopment Analysis and Malmquist Productivity Index in the Development of Human Capital of ASEAN-5 Countries*, "Thailand and the World Economy", 41 (3), pp. 88–101, https://so05.tci-thaijo.org/index.php/TER/article/view/267629

Suwanhirunkul, S., Suwanhirunkul, P., (2025), *Trade openness and economic growth: the role of financial development in ASEAN countries*, "South Asian Journal of Macroeconomics and Public Finance", 14 (2), pp. 260–280.

Tasane, H., Srun, S. (2023), *The Institutional Environment, Human Capital Development, and Productivity-Enhancing Factors: Evidence from ASEAN Countries*, "TRaNS: Trans-Regional and -National Studies of Southeast Asia", 11 (2), pp. 159–174, https://doi.org/10.1017/trn.2022.13

Thach, N.N. (2025), *Human capital's dual impact: advancing innovation and technology diffusion in ASEAN-5 through the Nelson-Phelps-Romer lens*, "PLOS ONE", 20 (11), e0333784, https://doi.org/10.1371/journal.pone.0333784

Tsaurai, K., Ndou, A. (2019), *Infrastructure, Human Capital Development and Economic Growth in Transitional Countries*, "Comparative Economic Research", 22 (1), pp. 33–52, https://doi.org/10.2478/cer-2019-0003

Wahyudi, H., Mulyya, A.P., Husain, F.R., Palupi, W.A. (2023), *Basic Infrastructure and Economic Growth in Sumatra Province, Indonesia*, "WSEAS Transactions on Systems", 22, pp. 73–86, https://doi.org/10.37394/23202.2023.22.9

Wang, Y., Lee, H.W., Tang, W., Whittington, J., Qiang, M. (2021), *Structural Equation Modeling for the Determinants of International Infrastructure Investment*, "Journal of Management in Engineering", 37 (4), 04021033, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000933

Zergawu, Y.Z., Walle, Y.M., Giménez-Gómez, J.-M. (2020), *The joint impact of infrastructure and institutions on economic growth*, "Journal of Institutional Economics", 16 (4), pp. 481–502, https://doi.org/10.1017/S1744137420000016