Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Structural Complementarity, Bottlenecks, and Total Factor Productivity in Mexico (2000–2025): A Matrix and Critical Political Economy Approach

Alan Alberto Ramírez-Guevara

alan.ramirezgv@uanl.edu.mx

Universidad Autónoma de Nuevo León

Carlos Adrian Cortez-Martínez

Universidad Autónoma de Nuevo León

Research Article

Keywords: Total Factor Productivity, O-Ring Complementarity, Liebig's Law, Critical Political Economy, Threshold Models, System GMM, Global Value Chains, Nearshoring

Posted Date: November 16th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11706417/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Structural Complementarity, Bottlenecks, and Total Factor Productivity in Mexico (2000–2025): A Matrix and Critical Political Economy Approach

Abstract

Traditional modeling of regional economic growth and Total Factor Productivity (TFP) in emerging economies has relied on continuous neoclassical specifications assuming unitary elasticity of substitution. This paper demonstrates the analytical insufficiency of such frameworks to explain persistent subnational divergence across Mexico, where localized human capital accumulation fails to mechanically translate into proportional technical efficiency gains. Engaging in critical dialogue with evolutionary and radical political economy, we examine the fundamental epistemological tensions underlying aggregate capital and TFP accounting, formalizing a multidimensional matrix architecture that synthesizes Kremer's (1993) O-Ring production theory, Liebig's Law of the Minimum, input-output shock propagation through intersectoral networks (Acemoglu et al., 2012), and power asymmetries across Global Value Chains (Kapeller et al., 2024; Durand & Milberg, 2020). Utilizing the Adjusted Mazziotta-Pareto Index (AMPI), internal horizontal disparities across complex labor skills and critical infrastructure vectors are penalized non-compensatorily. Coupled Leontief inverse matrices derive sector-specific co-requirement structures, projecting realized factor absorption. Furthermore, applying local projections (Jordà, 2005) across five historical macroeconomic disruptions, we derive normative resilience matrices via Moore-Penrose pseudoinverses, auditing spatial mismatch through Mahalanobis distances and cosine similarity. Panel threshold regressions (Hansen, 1999) empirically validate the bottleneck hypothesis: the marginal return on technical skills is statistically indistinguishable from zero in states below the critical infrastructure threshold ($\gamma_1 = 92.40$), switching to a highly significant regime once surpassed ($\theta_2 = 0.428$, $p < 0.001$). Two-step System GMM dynamic panel estimations with Windmeijer (2005) correction confirm structural supermodularity ($\beta_3 = 0.015$, $p < 0.001$) and significant penalties from Mahalanobis mismatch ($\beta_4 = -0.142$, $p < 0.001$). We deconstruct the *nearshoring* phenomenon through the lenses of capital's spatial fix (Harvey, 2001), the maquiladora regime and labor market segmentation (Delgado Wise & Cypher, 2007; Marini, 1973), as well as biophysical boundaries

and ecologically unequal exchange (Althouse et al., 2023; Obeng-Odoom, 2025). Finally, we categorize Mexico's 32 states into four operational quadrants, contrasting conventional technocratic policy prescriptions with sovereign planning strategies for regional development.

Keywords: Total Factor Productivity, O-Ring Complementarity, Liebig's Law, Critical Political Economy, Threshold Models, System GMM, Global Value Chains, Nearshoring.
JEL Classification: O47, R11, C23, D57, B51.

1. Introduction and Problem Statement

The persistence of marked disparities in development levels and Total Factor Productivity (TFP) across Mexico's regions constitutes one of the most relevant structural puzzles in contemporary applied economics. Over the past three decades, several federal entities have substantially increased their formal schooling rates, higher education enrollment, and the aggregate supply of professionals. However, this accumulative effort has not mechanically translated into a proportional acceleration of technical productivity or sustained subnational economic convergence.

At the core of this issue lies the analytical inadequacy of traditional neoclassical growth theory. By assuming continuous production functions—typically of the Cobb-Douglas or Constant Elasticity of Substitution (CES) family with unitary or constant substitution elasticities—conventional models postulate that a deficit in physical assets or enabling networks (electricity, natural gas, logistical connectivity) can be offset by a larger endowment of generic labor or human capital. In the context of complex manufacturing activities and global industrial services, this axiom of perfect substitutability is refuted by empirical reality: a high-tech industrial plant cannot compensate for the lack of continuous high-voltage electrical supply or customs congestion simply by adding more engineers to its payroll.

The presence of network indivisibilities and technical rigidities demands a reformulation of regional analysis under a strict complementarity framework. When production inputs operate complementarily, the overall productivity of the economic system becomes constrained by the performance of its most lagging component. Localized frictions generated by bottlenecks in critical infrastructure or deficits in specialized technical skills do not remain confined to the unit experiencing them; rather, they propagate across intersectoral value chains, eroding aggregate macroeconomic efficiency.

The objective of this paper is to develop, formalize, and calibrate a comprehensive econometric protocol to quantify structural complementarities, identify bottlenecks through non-linear threshold models, and estimate the impact of factor mismatch gaps on TFP across Mexico's 32 federal entities from 2000 to the present.

However, as contemporary evolutionary and critical political economy literature cautions (Beckenbach, 2020; Cincotti et al., 2020; Passos & Morlin, 2021), a rigorous analysis of productivity cannot be reduced to the formal modeling of aseptic technical constraints. The persistence of regional underdevelopment, network disarticulation, and spatial bottlenecks are not mere market accidents, but historical outcomes of Mexico's subordinate integration into the international division of labor, the consolidation of a dependent maquiladora regime, and the asymmetric extraction of economic surplus (Cypher & Delgado Wise, 2012; Marini, 1973).

2. Theoretical and Conceptual Framework: Dialogue between Structural Econometrics and Critical Political Economy

2.1 Kremer's (1993) O-Ring Production Theory

The formalization of strict complementarity processes draws on the O-Ring production model proposed by Kremer (1993). In this formulation, the production process consists of a sequence of n indispensable tasks or inputs, where final output is proportional to the product of the execution quality or success probability of each component:

$$Y = K^{\alpha} \left(\prod_{i=1..n} q_i\right) n\, B$$

Where $q_i \in [0, 1]$ denotes the quality or efficiency rate of task i, K represents physical capital, and B is a technological scale parameter. The essential mathematical property of this formulation is the supermodularity of the production function with respect to factor qualities:

$$\partial^2 Y \,/\, (\partial q_i \, \partial q_j) > 0, \forall\, i \neq j$$

This strictly positive cross-derivative implies that the marginal return to increasing the quality of an input rises as the quality of all other inputs increases. As an immediate

distributional outcome, the model predicts positive assortative matching: high-quality inputs concentrate in environments where complementary factors are equally advanced. Conversely, if a single input exhibits zero or severely degraded quality ($q_k \rightarrow 0$), total system output collapses toward zero, regardless of the sophistication or abundance of the remaining n - 1 components (Kremer, 1993).

From an evolutionary political economy perspective, this assortative matching assumes a historical-structural dimension: it operates as the microeconomic driver of Myrdalian circular cumulative causation and spatial polarization (Rama & Hall, 2021). Large transnational capital concentrates investment in subnational enclaves endowed with state-subsidized infrastructure, draining skilled labor and resources from lagging hinterlands and perpetuating structural heterogeneity (Pinto, 1998).

2.2 The Limiting Factor Principle and Liebig's Law of the Minimum

At the subnational macroeconomic level, the biophysical counterpart to the O-Ring model is found in Liebig's Law of the Minimum. According to this principle, crop growth is governed not by the total resources available, but by the limited nutrient relative to the plant's metabolic requirements.

In production theory, this principle is formalized via non-differentiable, fixed-coefficient Leontief technologies:

$$Y = \min \{x_1 / a_1, x_2 / a_2, \ldots, x_m / a_m\}$$

Under this production structure:

$$\partial Y / \partial x_i = 0 \text{ if } x_i / a_i > \min_{j \neq i} \{ x_j / a_j \}$$

The marginal product of any input x_i exceeding the critical ratio determined by the limiting factor is exactly zero. Applied to regional development in Mexico, Liebig's Law explains why government subsidies or training programs remain ineffective if recipient states lack the minimum threshold of enabling physical infrastructure.

Reinterpreted through structuralist political economy, Liebig's Law reflects the *intersectoral disarticulation* analyzed by Samir Amin: while core economies organically articulate the production of capital goods (Department I) and consumer goods (Department II), peripheral

economies exhibit fractures in their internal technical matrix, where critical network bottlenecks are not temporary market failures but structural features of neoliberal public investment retrenchment (Cypher & Delgado Wise, 2010).

2.3 Network Propagation of Disturbances (Acemoglu et al., 2012) and GVC Asymmetries

The connection between subnational factor mismatches and aggregate macroeconomic dynamics draws on the theory of input-output network shock propagation developed by Acemoglu, Carvalho, Ozdaglar, and Tahbaz-Salehi (2012). Rejecting Lucas' classical diversification argument regarding the irrelevance of microeconomic shocks, Acemoglu et al. (2012) demonstrate that when input-output matrices exhibit asymmetric topologies dominated by central hub sectors, localized bottlenecks do not wash out but amplify across the productive web.

If key manufacturing sectors depend on intermediate inputs from core infrastructure sectors with low substitutability (electricity, rail transport, gas distribution), localized disruptions in these hub nodes produce cascade effects that contract the national production possibilities frontier (Acemoglu et al., 2012).

However, as Kapeller, Gräbner-Radkowitsch, and Hornykewycz (2024) point out, Acemoglu et al.'s network topology assumes an institutional neutrality that masks asymmetric power relationships. Global Value Chains (GVCs) operate as transnational hierarchies governed by lead corporations that dictate competition terms to peripheral suppliers. This dynamic aligns with the intellectual monopoly literature (Durand & Milberg, 2020; Auvray et al., 2021): core lead firms monopolize patents, software, and intangible assets, offloading energy-, water-, and physical infrastructure-intensive assembly tasks to the periphery.

2.4 Critical Deconstruction of the Aggregate Production Function and TFP: The Accounting Identity Fallacy

Relying on Total Factor Productivity as an unexamined metric of technical efficiency introduces a fundamental methodological flaw. Since the Cambridge Capital Controversy, led by Joan Robinson and Piero Sraffa, it has been established that constructing an aggregate physical capital stock (K) independently of relative prices and income distribution is logically impossible (Harcourt, 1972). Aggregating heterogeneous capital goods requires prior knowledge of the profit rate (r) and wage rate (w), incurring irrecoverable circularity.

Anwar Shaikh (1974) extended this critique empirically via the "humbug production function," showing that high coefficients of determination (R^2) in aggregate production functions do not confirm technological laws, but simply replicate underlying accounting identities. Felipe and McCombie (2007, 2013, 2014) formalized this argument by demonstrating that gross value added (V_t) equals the sum of total wage bill and gross operating surplus:

$$V_t \equiv w_t L_t + r_t J_t$$

Where w_t is the average real wage, L_t is employment, r_t is the average profit rate, and J_t is the constant-price valuation of capital stock. Differentiating fully with respect to time:

$$\hat{V_t} \equiv a_t \hat{r_t} + (1 - a_t) \hat{w_t} + a_t \hat{J_t} + (1 - a_t) \hat{L_t}$$

Where $a_t = (r_t J_t) / V_t$ and $1 - a_t = (w_t L_t) / V_t$ represent capital and labor income shares. Comparing this identity with standard Solow residual calculations reveals their algebraic equivalence:

$$\lambda_t \equiv a_t \hat{r_t} + (1 - a_t) \hat{w_t}$$

The Solow residual does not capture purely exogenous technical progress, but a weighted average of income distribution dynamics between wages and profits, heavily conditioned by capacity utilization, surplus extraction, and monopoly markups (Felipe & McCombie, 2014; Shaikh, 1974).

As Beckenbach (2020) argues in the *Review of Evolutionary Political Economy* (REPE), productive systems must be understood through a dynamic theory of value where production is not a neutral optimizing black box, but a social process centered on generating and realizing surplus value (*s*) from wage labor (*v*). Consequently, empirical TFP measurements across Mexican states reflect capacity utilization fluctuations, profit rate shifts, monopoly rents, and intersectoral/international trade imbalances.

Analytical Dimension	Traditional Neoclassical Paradigm (KLEMS / Solow)	Critical Political Economy Perspective (REPE / Heterodoxy)
Nature of Capital (K)	Homogeneous, physical technical factor fully substitutable along smooth isocquants.	Valorized social relation of production; aggregation depends on distribution (w, r).
Meaning of TFP	Direct metric of exogenous technical progress or neutral efficiency gains.	Artifact of distributive accounting identity ($a \cdot \hat{r} + (1-a) \cdot \hat{w}$) driven by markups.
Market Structure	Neutral network for efficient resource allocation governed by equilibrium prices.	Contested hierarchy governed by corporate monopolies, power asymmetries, and distributional conflict.
Production Chains	Technical optimization networks of intersectoral intermediate inputs.	Global Value Chains structured to extract peripheral surplus and intellectual monopoly rents.
Regional Disparities	Temporary spatial friction solvable via flexible prices and factor mobility.	Historical structural heterogeneity, uneven development, and dependent accumulation.

3. Fundamental Theoretical and Econometric Assumptions

The protocol rests on five structural assumptions:

- **Assumption 1 (Additive Non-Compensability)**: The dimensions comprising the labor skills vector (H_{rt}) and critical infrastructure vector (I_{rt}) are not perfectly substitutable. Additive linear averages are rejected in favor of non-compensatory penalization of intra-entity variance via the AMPI approach (Mazziotta & Pareto, 2016).
- **Assumption 2 (Exogenous Shock Identification and Invariance)**: Evaluated macroeconomic shocks (1995 Tequila Crisis, 2008–2009 Great Recession, 2016–2019

USMCA Uncertainty, 2020–2021 COVID-19 Pandemic, and 2022–present Nearshoring Demand) are exogenous to contemporaneous subnational factor accumulation decisions, identifying unbiased impulse-response paths via local projections (Jordà, 2005).

- **Assumption 3 (Markovian Stochastic Process of Latent Productivity)**: Unobserved technical productivity ω_{ist} follows a first-order Markov process $E[\omega_{ist} \mid \omega_{is,t-1}] = f(\omega_{is,t-1}) + \xi_{ist}$, where the stochastic innovation ξ_{ist} is uncorrelated with past capital investment or lagged intermediate inputs (Wooldridge, 2009).
- **Assumption 4 (Existence of Non-Linear Threshold Regimes)**: The functional relationship between TFP and factor endowments features structural regime shifts driven by endogenous cutoff parameters (γ_1 and γ_2). Following Hansen (1999), the threshold search space is restricted to the interquartile range [0.15, 0.85] to ensure adequate test power.
- **Assumption 5 (Sequential Exogeneity and Moment Conditions in Dynamic Panels)**: Lagged endogenous variables in levels are orthogonal to first-differenced error terms, and lagged differenced regressors are orthogonal to time-invariant state fixed effects, satisfying System GMM conditions (Arellano & Bover, 1995; Blundell & Bond, 1998; Roodman, 2009).

4. Methodological Protocol and Matrix Architecture

The methodology operates over a three-dimensional dataset indexed by federal entities $r \in \{1, ..., 32\}$, SCIAN subsectors $s \in \{1, ..., S\}$, and annual periods $t \in [2000, 2024]$.

4.1 Variable Inventory, Microdata, and Goalposts

The labor skills vector (H_{rt}) aggregates three pillars constructed from ENE (2000–2004) and ENOE (2005–present) microdata:

1. **H_1 (STEM Specialization)**: Share of employed workforce with higher education in science, technology, engineering, and mathematics.
2. **H_2 (SINCO Technical Qualification)**: Share of employment in SINCO skill levels 3 and 4 (professionals, technicians, and managers).
3. **H_3 (Mincerian Wage Returns)**: Marginal return to formal education estimated annually by state using Heckman selection models:

$$\ln W_{irt} = \alpha_{rt} + \beta_{rt}^{Mincer} S_{irt} + \gamma_1 Exp_{irt} + \gamma_2 Exp_{irt}^2 + X_{irt}'\Gamma + \lambda_{Heckman} \hat{\lambda}_{irt} + \varepsilon_{irt}$$

Where $\hat{\lambda}_{irt}$ denotes the inverse Mills ratio calculated from the first-stage probit selection equation to control for formal labor market selection bias.

The critical infrastructure vector (I_{rt}) integrates four administrative pillars:

1. **I_1 (Energy & Gas)**: Substation transformer capacity per industrial area (MVA/km²) from PRODESEN (CENACE/SENER) and Sistrangas natural gas flow access (CENAGAS/CRE).
2. **I_2 (Logistics & Transport)**: Paved 4+ lane federal highway density weighted by the inverse International Roughness Index (SICT), double-stack rail density (ARTF), and customs clearance times (ANAM).
3. **I_3 (Sustainable Water Availability)**: Industrial groundwater extraction concessions in non-deficit aquifers (REPDA/CONAGUA) and treated industrial wastewater capacity (L/s).
4. **I_4 (Digital Connectivity)**: Fixed Broadband subscriptions >100 Mbps per 1,000 firms and trunk fiber-optic network mileage (IFT).

All indicators are normalized against invariant historical goalposts:

Dimension	Operational Pillar	Base Indicator	Primary Source	Polarity	Minimum Boundary (Min_j)	Maximum Boundary (Max_j)
Skills	H_1	STEM Occupied / Total EAP	ENOE (INEGI)	Positive (+)	0.00%	25.00%
Skills	H_2	SINCO Levels 3-4 Employment	ENOE (INEGI)	Positive (+)	5.00%	45.00%
Skills	H_3	Mincerian Wage Return	ENOE Microdata	Positive (+)	0.02	0.16
Infrastructure	I_1	Substation Capacity Density	PRODESEN / CENACE	Positive (+)	0.00	12.50 MVA/km²

Dimension	Operational Pillar	Base Indicator	Primary Source	Polarity	Minimum Boundary (Min_j)	Maximum Boundary (Max_j)
Infrastructure	I_2	Highway Density & Inv. IRI	SICT / ARTF	Positive (+)	0.00	1.00 Index
Infrastructure	I_3	Groundwater Concession Vol.	REPDA (CONAGUA)	Positive (+)	0.00	450.00 hm^3
Infrastructure	I_4	High-Speed Corporate FBB	BIT (IFT)	Positive (+)	0.00	850.00 Subs/1k

4.2 Non-Linear Normalization: Adjusted Mazziotta-Pareto Index (AMPI)

Indicators are standardized onto a target mean of 100 within a [70, 130] range:

$$z_{ijrt} = 100 + 60 \cdot [(x_{ijrt} - Min_j) / (Max_j - Min_j)]$$

For negative polarity variables (e.g., customs clearance delays), standardizations are inverted:

$$z_{ijrt} = 100 + 60 \cdot [(Max_j - x_{ijrt}) / (Max_j - Min_j)]$$

Intra-entity moments (mean $\bar{z}_{rt}$, standard deviation $s_{z,rt}$, coefficient of variation $cv_{rt} = s_{z,rt} / \bar{z}_{rt}$) determine the synthetic AMPI score:

$$c_{rt} = \bar{z}_{rt} - s_{z,rt} \cdot cv_{rt}$$

The penalty term $s_{z,rt} \cdot cv_{rt}$ imposes a non-linear quadratic penalty for internal imbalance: between two states with identical average scores, the state suffering an acute bottleneck in a single critical dimension receives a lower score, operationalizing Liebig's Law (Mazziotta & Pareto, 2016).

4.3 Denton-Cholette Quadratic Temporal Disaggregation

To reconcile industry classification shifts prior to 2004, probabilistic transition matrices are estimated between CMAP 1994 and SCIAN (2002–2018 editions) using dual-coded 2004 Economic Census microdata (INEGI, 2018, 2024a).

Because fixed capital stock (K) and gross value added (Y) at the subnational industry level are captured quinquennially by Economic Censuses, quadratic Denton-Cholette temporal disaggregation is implemented (Denton, 1971; Dagum & Cholette, 2006). The method constructs an annual series $\hat{y}_t$ tracking high-frequency indicators p_t (gross fixed capital formation from National Accounts and construction value from ENEC), minimizing first-difference relative variance:

$$\min_{\hat{y}} \sum_{t=2..T} [(\hat{y}_t / p_t) - (\hat{y}_{t-1} / p_{t-1})]^2$$
$$\text{s.t. } \sum_{t \in \tau} \hat{y}_t = Y_\tau, \forall\, \tau \in \{1999, 2004, 2009, 2014, 2019, 2024\}$$

4.4 Leontief Bilinear Algebra and Realized Absorption Potential

The interaction between subnational human capital $H_{rt} \in \mathbb{R}^{1 \times K_H}$ and infrastructure $I_{rt} \in \mathbb{R}^{1 \times K_I}$ is modeled as a bilinear projection mediated by sector s's Co-requirement Technology Matrix $W_s \in \mathbb{R}^{K_H \times K_I}$:

$$M_{rst} = H_{rt}\, W_s\, I_{rt}^T$$

Empirically, W_s is constructed from direct and indirect intersectoral propagation structures derived from national Input-Output tables coupled with the Leontief inverse matrix (Acemoglu et al., 2012):

$$W_s = \Phi_H\, (I - A)^{-1}\, \Phi_I^T$$

Where A is the direct intermediate coefficient matrix, $(I - A)^{-1}$ is the Leontief inverse, and Φ_H, Φ_I are mapping operators projecting factor intensities onto skills and infrastructure spaces. The resulting matrix product M_{rst} measures effective subnational factor absorption.

Under GVC analysis, export-oriented manufacturing branches such as automotive (SCIAN 336) or electronics (SCIAN 334) display high technical multipliers in $(I - A)^{-1}$ alongside weak domestic linkages, importing key high-value components while transferring intellectual monopoly rents abroad (Cypher & Delgado Wise, 2012; Durand & Milberg, 2020).

4.5 Local Projections (Jordà, 2005) and Normative Resilience Matrix

The normative sector requirement matrix N_s is calibrated from historical subsector responses to exogenous macroeconomic shocks using local projections (Jordà, 2005):

$$y_{s,t+h} - y_{s,t-1} = \alpha_{s,h} + \beta_{s,h}^{e}\, \text{Shock}_t^{e} + \sum_{k=1..P} \gamma_{k,h}\, \Delta y_{s,t-k} + X_t' \Gamma_h + \varepsilon_{s,t+h},\ \forall\ h \in \{0, 1, \ldots, H\}$$

From estimated impulse response functions, two metrics are extracted:

1. **Contraction Amplitude**: $s_e = \min_{h\in[0,H]} (\psi_{s,h,e})$.
2. **Structural Hysteresis**: $h_e = \arg\min_{h\in[0,H]} \{h \mid \psi_{s,h,e} \geq 0\}$.

These values form the Sectoral Vulnerability Matrix $D_s \in \mathbb{R}^{E\times 2}$. The Normative Sector Requirement Matrix $N_s \in \mathbb{R}^{K_H\times K_I}$ is recovered via the Moore-Penrose pseudoinverse:

$$N_s = [D_s^T D_s]^{-1} D_s^T \Omega$$

Where Ω is a weight matrix mapping sectoral vulnerability metrics onto required factor intensities in the skills and infrastructure space.

4.6 Multivariate Structural Mismatch Metrics

The divergence between realized factor supply M_{rst} and normative resilience requirements N_s is evaluated using two metrics:

1. **Mahalanobis Distance (Φ_{rst})**: Accounts for the spatial covariance matrix Σ to correct for inter-factor collinearity:

$$\Phi_{rst} = \sqrt{[\ (\text{vec}(M_{rst}) - \text{vec}(N_s))'\ \Sigma^{-1}\ (\text{vec}(M_{rst}) - \text{vec}(N_s))\ ]}$$

2. **Cosine Similarity (A_{rst})**: Measures directional alignment independently of scale:

$$A_{rst} = \langle M_{rst}, N_s \rangle_F \ /\ (|M_{rst}|_F \cdot |N_s|_F) = \text{tr}(M_{rst}^T N_s) \ /\ (\sqrt{[\text{tr}(M_{rst}^T M_{rst})]}\ \sqrt{[\text{tr}(N_s^T N_s)]})$$

4.7 TFP Estimation Strategies

To ensure robustness, three concurrent TFP measures are estimated:

1. **Official Benchmark KLEMS**: State-level TFP series base 2018 compiled by INEGI (2024b).
2. **Spatial Solow Residual**:

$$\ln Y_{rst} = \beta_L \ln L_{rst} + \beta_K \ln K_{rst} + \rho_W W_{spat} \ln Y_{rst} + \ln TFP_{rst}$$

Where W_{spat} is a row-standardized spatial weight matrix of first-order geographic contiguity.
3. **Wooldridge (2009) Control Function GMM**: Controls for input endogeneity using energy inputs m_{ist} as proxy instruments, approximating unobserved productivity via 3rd-degree Chebyshev polynomials:

$$\ln TFP_{rst} = y_{rst} - \beta_l l_{rst} - \beta_k k_{rst}$$

4.8 Non-Linear Panel Threshold Regressions (Hansen, 1999)

Liebig's Law is formally tested via fixed-effects panel threshold models:

$$\ln TFP_{rst} = \mu_{rs} + \delta_t + \theta_1 H_{rt} \cdot \mathbb{1}(I_{rt} \leq \gamma) + \theta_2 H_{rt} \cdot \mathbb{1}(I_{rt} > \gamma) + X_{rst}'\Gamma + \varepsilon_{rst}$$

The threshold parameter γ is endogenously identified by minimizing the concentrated sum of squared residuals: $\hat{\gamma} = \arg\min_\gamma S_1(\gamma)$. Significance of the likelihood ratio statistic $F_1 = (S_0 - S_1(\hat{\gamma})) \,/\, \hat{\sigma}^2$ is evaluated using a non-parametric bootstrap with 5,000 replications (Hansen, 1999). Liebig's hypothesis requires:

$$\theta 1 \approx 0 (\text{statistically insignificant}) \wedge \theta_2 > 0` (\text{significant at } p < 0.01)$$

Symmetrically, a dual specification evaluates human capital as the transition variable governing infrastructure returns:

$$\ln TFP_{rst} = \mu_{rs} + \delta_t + \psi_1 I_{rt} \cdot \mathbb{1}(H_{rt} \leq \lambda) + \psi_2 I_{rt} \cdot \mathbb{1}(H_{rt} > \lambda) + X_{rst}'\Gamma + u_{rst}$$

4.9 Dynamic Panel: Two-Step System GMM

To address dynamic persistence, unobserved heterogeneity, and potential endogeneity, we fit a two-step System GMM model (Arellano & Bover, 1995; Blundell & Bond, 1998) with Windmeijer (2005) finite-sample corrected standard errors:

$$\ln TFP_{rst} = \alpha \ln TFP_{rs,t-1} + \beta_1 H_{rt} + \beta_2 I_{rt} + \beta_3 (H_{rt} \times I_{rt}) + \beta_4 \Phi_{rst} + Z_{rst}'\Theta + \mu_{rs} + \delta_t + \varepsilon_{rst}$$

The multiplicative term $H_{rt} \times I_{rt}$ tests O-Ring supermodularity ($\beta_3 > 0$), while Φ_{rst} captures structural mismatch penalties ($\beta_4 < 0$).

5. Empirical Calibration and Results Discussion

5.1 Econometric Evidence of Bottlenecks (Hansen, 1999 Threshold Model)

The primal threshold model estimates an infrastructure cutoff at $\hat{\gamma}_1 = 92.40$ (standard error = 1.85), yielding a bootstrap F_1 statistic of 38.65 ($p < 0.001$), well above the 1% critical value (21.40) and rejecting linearity.

Threshold Model	Parameter	Coefficient	Std. Error	*t*-statistic	*p*-value	Theoretical Interpretation
Primal: Infrastructure	Regime 1: θ_1 ($I \leq \gamma_1$)	0.041	0.082	0.50	0.617	Zero marginal return to skills (Liebig)
Primal: Infrastructure	Regime 2: θ_2 ($I > \gamma_1$)	0.428	0.065	6.58	< 0.001***	Full return to technical skills
Primal: Infrastructure	Regime Shift ($\theta_2 - \theta_1$)	$\theta_2 - \theta_1 = 0.387$	0.098	3.95	< 0.001***	Significant regime structural shift
Dual: Human Capital	Regime 1: ψ_1 ($H \leq \gamma_2$)	0.023	0.075	0.31	0.758	Zero marginal return to infrastructure
Dual: Human Capital	Regime 2: ψ_2 ($H > \gamma_2$)	0.384	0.059	6.51	< 0.001***	Full return to physical infrastructure

Threshold Model	Parameter	Coefficient	Std. Error	t-statistic	p-value	Theoretical Interpretation
Dual: Human Capital	Threshold Cutoff (γ_2)	96.10	2.10	45.76	< 0.001***	Skill threshold for infrastructure return

These findings confirm Liebig's Law of the Minimum: in states below the infrastructure cutoff of 92.40, expanding technical education yields not statistically significant TFP gain. Symmetrically, industrial infrastructure investments remain unproductive unless local human capital exceeds $\hat{\gamma}_2 = 96.10$.

In structuralist terms (Pinto, 1970; Prebisch, 1950), $\hat{\gamma}_1 = 92.40$ marks the threshold of *structural heterogeneity*: states below this line remain excluded from dynamic accumulation, constrained not by labor quality per se, but by missing enabling conditions.

5.2 Panel Dynamics and Diagnostic Validation (System GMM)

The dynamic System GMM model confirms structural inertia and network complementarities:

$$\ln TFP_{rst} = \alpha \ln TFP_{rs,\,t-1} + \beta_1 H_{rt} + \beta_2 I_{rt} + \beta_3 (H_{rt} \times I_{rt}) + \beta_4 \Phi_{rst} + Z_{rst}'\Theta + \mu_{rs} + \delta_t + \varepsilon_{rst}$$

- **TFP Persistence ($\alpha = 0.582$, $p < 0.001$)**: Productivity displays strong path dependence; technical efficiency gains require sustained, long-term accumulation.
- **O-Ring Supermodularity ($\beta_3 = 0.015$, $p < 0.001$)**: The interaction term is positive and statistically significant, confirming that factor returns increase with the quality of complementary inputs.
- **Mahalanobis Mismatch Penalty ($\beta_4 = -0.142$, $p < 0.001$)**: Each unit of structural distance from the normative resilience matrix reduces state TFP by 14.2%, measuring the real cost of spatial misallocation.
- **Diagnostic Tests**: Arellano-Bond tests report $z = -3.85$ ($p < 0.001$) for AR (1) and $z = 0.42$ ($p = 0.674$) for AR (2), confirming the absence of second-order serial correlation. The Hansen overidentification test ($J = 24.18$, $p = 0.285$) and Difference-in-Hansen test ($C = 5.12$, $p = 0.398$) validate the instrument set.

5.3 Spatial Taxonomy and Critical Reinterpretation of the Four Quadrants

Mapping Mexican states against empirical thresholds (γ_1 = 92.40, γ_2 = 96.10) generates a subnational taxonomy:

Quadrant	Factor Profile	Limiting Bottleneck	Representative States	Dominant Elasticity	Investment Priority
I. Infrastructure Deficit	$H > \gamma_2$, $I \leq \gamma_1$	Power grid, gas supply, logistics	NL, COAH, QRO, CHIH, TAMPS, GTO, SLP, SON, BC	Infrastructure (θ_2 = 0.384)	Grid capacity, substations, gas pipelines
II. Skill Deficit	$H \leq \gamma_2$, $I > \gamma_1$	STEM engineers, technicians	VER, TAB, TLAX, ZAC, DGO, CAMP, COL, NAY	Skills (θ_2 = 0.428)	Technological institutes, vocational training
III. Structural Trap	$H \leq \gamma_2$, $I \leq \gamma_1$	Dual factor constraint	CHIS, GRO, OAX, PUE (regions), HGO, MICH	Insignificant (θ_1 = 0.041 / 0.023)	Joint infrastructure & educational packages
IV. Factorial Synchrony	$H > \gamma_2$, $I > \gamma_1$	None (frontier optimization)	CDMX, MEX, AGS, JAL, YUC, BCS, QROO, SIN	Dual Full Returns	R&D centers, advanced tech, circular water

Critical political economy deconstructs these groupings (Cypher & Delgado Wise, 2012; Delgado Wise & Cypher, 2007; Marini, 1973):

- **Quadrant I (Maquila Enclaves)**: States like Nuevo León, Coahuila, and Querétaro host export plants reliant on imported inputs (>85%), where saturated grids reflect lead firms socializing infrastructure costs.
- **Quadrant II (Extractivist Enclaves)**: States like Veracruz, Tabasco, and Campeche experience resource extraction without local technological spillover.
- **Quadrant III (Labor Reserves)**: Chiapas, Oaxaca, and Guerrero function as low-wage labor reserves for northern and central agricultural and industrial sectors.
- **Quadrant IV (Metropolitan Command)**: Concentrates corporate headquarters, financial services, and administrative nodes governing external integration.

5.4 Political Ecology and Biophysical Limits of Nearshoring

Including water infrastructure (I_3) highlights ecological boundaries that standardized indices can obscure. As Obeng-Odoom (2025) notes, global supply chain expansion often induces *ecologically unequal exchange* (Althouse et al., 2023), transferring water- and energy-intensive manufacturing to peripheral regions.

In arid northern states (Nuevo León, Coahuila, Sonora), industrial groundwater concessions conflict directly with residential access. Here, the binding constraint is not merely infrastructure, but ecological carrying capacity—illustrating James O'Connor's second contradiction of capitalism: the degradation of environmental conditions required for ongoing capital accumulation.

6. Conclusions and Policy Implications for Nearshoring

Our findings call for a fundamental reassessment of regional development policy amid current nearshoring trends:

First, nearshoring should not be viewed as an automatic engine of regional convergence. Rather, it represents a spatial fix (Harvey, 2001) driven by lead firms seeking cost reductions and geopolitical realignments, which risks reinforcing dependent export-enclave patterns (Cypher & Delgado Wise, 2012).

Second, generic tax incentives and passive investment attraction are inadequate. Under O-Ring complementarities, subsidizing investment in regions with unaddressed bottlenecks yields negligible productivity returns. Effective regional policy requires coordinated public planning, using input-output mismatch metrics to guide strategic investments.

Regional Quadrant	Standard Technocratic Recommendation	Sovereign & Critical Development Alternative
Quadrant I: Infrastructure Deficit	Private power grid expansion to accommodate nearshoring assembly plants.	**Public Energy Sovereignty & Environmental Governance**: Tie industrial permitting to aquifer capacity and tax monopoly rents to fund public energy transitions.
Quadrant II: Skill Deficit	Vocational curriculum adjustments tailored to multinational assembly requirements.	**Endogenous Technological Capacity**: Expand public research universities and direct R&D toward strategic state industries.
Quadrant III: Structural Trap	Basic educational grants and basic infrastructure subsidies.	**Structural Reform & Food Sovereignty**: Regional public investment packages, support for local agriculture, and autonomous regional value chains.
Quadrant IV: Factorial Synchrony	Subsidized private innovation hubs and 5G network rollouts.	**Public Intellectual Commons**: Open-access technology hubs in microelectronics/biomedicine, redirecting metropolitan surpluses to lagging regions.

Overcoming regional disparities across Mexico's subnational units requires moving beyond passive tax-incentive models toward a strategy focused on productive, energetic, and environmental sovereignty, ensuring that productivity gains translate into broad-based social development.

References

Acemoglu, D., Carvalho, V. M., Ozdaglar, A., & Tahbaz-Salehi, A. (2012). The network origins of aggregate fluctuations. Econometrica, 80(5), 1977–2016. https://doi.org/10.3982/ECTA9623

Ackerberg, D. A., Caves, K., & Frazer, G. (2015). Identification properties of recent production function estimators. *Econometrica*, 83(6), 2411–2451. https://doi.org/10.3982/ECTA13408

Agencia Reguladora del Transporte Ferroviario. (2024). Anuario estadístico ferroviario 2023. Secretaría de Infraestructura, Comunicaciones y Transportes.

Althouse, J., Cahen-Fourot, L., Carballa-Smichowski, B., Durand, C., & Knauss, S. (2023). Ecologically unequal exchange and uneven development patterns along global value chains. World Development, 170, 106308. https://doi.org/10.1016/j.worlddev.2023.106308

Arellano, M., & Bover, O. (1995). Another look at the instrumental variable estimation of error-components models. Journal of Econometrics, 68(1), 29–51. https://doi.org/10.1016/0304-4076(94)01642-D

Auvray, T., Durand, C., Rabinovich, J., & Rikap, C. (2021). Corporate financialization's conservation and transformation: from Mark I to Mark II. Review of Evolutionary Political Economy, 2(3), 431–457. https://doi.org/10.1007/s43253-021-00045-4

Banco de México. (2024). Reporte de estabilidad financiera. Banco de México.

Beckenbach, F. (2020). A value-theoretic approach to economic dynamics and evolution—synthesizing different Marxian modules in a simulation model. Review of Evolutionary Political Economy, 1(1), 103–135. https://doi.org/10.1007/s43253-020-00007-2

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

Centro Nacional de Control de Energía. (2024). *Programa de desarrollo del sistema eléctrico nacional (PRODESEN) 2024–2038*. Secretaría de Energía.

Cincotti, S., Elsner, W., Lazaric, N., Nesvetailova, A., & Stockhammer, E. (2020). Towards an evolutionary political economy. Editorial to the inaugural issue of the Review of Evolutionary Political Economy REPE. *Review of Evolutionary Political Economy*, 1(1), 1–12. https://doi.org/10.1007/s43253-020-00011-6

Comisión Federal de Competencia Económica. (2021). Estudio sobre la competencia en el servicio público de transporte ferroviario de carga. COFECE.

Comisión Nacional del Agua. (2024). *Registro Público de Derechos de Agua* (REPDA). SEMARNAT.

Cypher, J. M., & Delgado Wise, R. (2010). Mexico's Economic Dilemma: The Developmental Failure of Neoliberalism. Rowman & Littlefield / Bloomsbury.

Dagum, E. B., & Cholette, P. A. (2006). Benchmarking, Temporal Distribution, and Reconciliation Methods for Time Series. Springer New York.

De Muro, P., Mazziotta, M., & Pareto, A. (2011). Composite indices of development and poverty: An application to MDGs. Social Indicators Research, 104(1), 1–18.

Delgado Wise, R., & Cypher, J. M. (2005). *The strategic role of labor in Mexico's subordinated integration into the U.S. production system under* NAFTA. Red Internacional de Migración y Desarrollo, Working Paper 2005-01.

Delgado Wise, R., & Cypher, J. M. (2007). The reshaping of Mexican labor exports under NAFTA: Paradoxes and challenges. *International Migration Review*, 41(3), 656–679.

Denton, F. T. (1971). Adjustment of monthly or quarterly series to annual totals: An approach based on quadratic minimization. *Journal of the American Statistical Association*, 66(333), 99–102.

Durand, C., & Milberg, W. (2020). Intellectual monopoly in global value chains. *Review of International Political Economy*, 27(2), 404–429. https://doi.org/10.1080/09692290.2019.1660703

Felipe, J., & McCombie, J. S. (2007). Is a theory of total factor productivity really needed? Metroeconomica, 58(1), 195–229.

Felipe, J., & McCombie, J. S. L. (2013). *The Aggregate Production Function and the Measurement of Technical Change: Not Even Wrong*. Edward Elgar Publishing.

Felipe, J., & McCombie, J. S. L. (2014). The aggregate production function: Not even wrong. *Review of Political Economy*, 26(1), 60–84. https://doi.org/10.1080/09538259.2013.874192

Hansen, B. E. (1999). Threshold effects in non-dynamic panels: Estimation, testing, and inference. Journal of Econometrics, 93(2), 345–368. https://doi.org/10.1016/S0304-4076(99)00025-1

Harcourt, G. C. (1969). Some Cambridge controversies in the theory of capital. Journal of Economic Literature, 7(2), 369–405.

Harvey, D. (2001). Globalization and the "spatial fix". *Geographische Revue*, 3(2), 23–30.

Instituto Federal de Telecomunicaciones. (2023). *Estudio de conectividad de banda ancha fija y costeo de redes de fibra óptica a nivel municipal en México*. IFT.

Instituto Federal de Telecomunicaciones. (2024). Diagnóstico del estado que guarda el Internet en México 2024. IFT.

Instituto Federal de Telecomunicaciones. (2025). *Cuaderno de indicadores 2025: Banco de Información de Telecomunicaciones (BIT)*. IFT.

Instituto Nacional de Estadística y Geografía. (2012). *Sistema Nacional de Clasificación de Ocupaciones (SINCO) 2011*. INEGI.

Instituto Nacional de Estadística y Geografía. (2018). *Sistema de Clasificación Industrial de América del Norte (SCIAN) México 2018*. INEGI.

Instituto Nacional de Estadística y Geografía. (2024a). *Censos Económicos: Metodología SAIC*. INEGI.

Instituto Nacional de Estadística y Geografía. (2024b). *Productividad Total de los Factores: Modelo KLEMS año base 2018*. INEGI.

Jordà, Ò. (2005). Estimation and inference of impulse responses by local projections. American Economic Review, 95(1), 161–182. https://doi.org/10.1257/0002828053828518

Kapeller, J., Gräbner-Radkowitsch, C., & Hornykewycz, A. (2024). Corporate power and global value chains: Current approaches for conceptualizing the power of multinationals. *Review of Evolutionary Political Economy*, 5(2), 371–397. https://doi.org/10.1007/s43253-024-00121-5

Kremer, M. (1993). The O-ring theory of economic development. The Quarterly Journal of Economics, 108(3), 551–575. https://doi.org/10.2307/2118400

Marini, R. M. (1973). Dialéctica de la dependencia. América Latina, dependencia y globalización, 107–150.

Mazziotta, M., & Pareto, A. (2016). On a generalized non-compensatory composite index for measuring socio-economic phenomena. *Social Indicators Research*, 127(3), 983–1003. https://doi.org/10.1007/s11205-015-0998-2

Obeng-Odoom, F. (2025). Ecology and power: From environmental and ecological economics to stratification economics. Review of Evolutionary Political Economy, 6(3), 499–514. https://doi.org/10.1007/s43253-025-00149-1

Passos, N., & Morlin, G. S. (2021). Growth models and comparative political economy in Latin America. Revue de la Régulation, 31(2), 1–32. https://doi.org/10.4000/regulation.21444

Pinto, A. (1998). Naturaleza e implicaciones de la "heterogeneidad estructural" de la América Latina. El Trimestre Económico, 37(145), 83–100.

Prebisch, R. (1950). The Economic Development of Latin America and Its Principal Problems. United Nations.

Rama, J., & Hall, J. (2021). Raúl Prebisch and the evolving uses of centre-periphery in economic analysis. Review of Evolutionary Political Economy, 2(2), 315–332. https://doi.org/10.1007/s43253-021-00036-5

Roodman, D. (2009). How to do xtabond2: An introduction to difference and system GMM in Stata. The Stata Journal, 9(1), 86–136. https://doi.org/10.1177/1536867X0900900106

Secretaría de Infraestructura, Comunicaciones y Transportes. (2018). Memoria documental: Programa de auscultación de la red carretera federal. SICT.

Secretaría de Infraestructura, Comunicaciones y Transportes. (2022). *Programa sectorial de comunicaciones y transportes 2020–2024: Informe de auscultación y regularidad internacional (IRI)*. SICT.

Shaikh, A. (1974). Laws of production and laws of algebra: The humbug production function. *The Review of Economics and Statistics*, 56(1), 115–120. https://doi.org/10.2307/1927538

Windmeijer, F. (2005). A finite sample correction for the variance of linear efficient two-step GMM estimators. *Journal of Econometrics*, 126(1), 25–51. https://doi.org/10.1016/j.jeconom.2004.02.005

Wise, R. D., & Cypher, J. M. (2007). The strategic role of Mexican labor under NAFTA: Critical perspectives on current economic integration. *The Annals of the American Academy of Political and Social Science*, 610(1), 119–142.

Wooldridge, J. M. (2009). On estimating firm-level production functions using proxy variables to control for unobservables. *Economics Letters*, 104(3), 112–114. https://doi.org/10.1016/j.econlet.2009.04.026