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The impact of strategic cost management and digital transformation on cost efficiency and bank performance in Iraqi banks

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Abstract

Analyzing a dataset of 22 Iraqi financial institutions across the 2008–2024 timeframe (yielding 286 bank-year points in an unbalanced panel), this paper investigates the relationship between financial results, cost efficiency, digital upgrades, and disclosure-based strategic cost management. The Strategic Cost Management Index (SCMI) evaluates practices like activity-based and time-driven costing, capacity management, target costing, cost-driver and value-chain analysis, life-cycle and quality costing, benchmarking, and channel or customer profitability. Meanwhile, the Digital Transformation Index (DTI) captures multiple dimensions including technological readiness, investment, infrastructure, service adoption, usage depth, and connectivity with national payment networks. The cost-to-income ratio (CIR) measures operational efficiency, whereas return on equity (ROE) and return on assets (ROA) track overall performance. Controlling for bank and year fixed effects, the econometric models demonstrate that elevated SCMI and DTI levels align with a reduced CIR alongside stronger ROE and ROA, with mean-centered interaction terms displaying the anticipated signs for profitability and efficiency. Additionally, a mediation analysis reveals significant indirect pathways operating via the CIR, and tests involving ownership variables point to more pronounced effects within privately owned institutions. Given the observational nature of the research and the reliance on public disclosures for the indices, the conclusions reflect conditional relationships rather than direct causality. Ultimately, the work offers a management-accounting perspective on how capacity choices, channel profitability metrics, cost-driver insights, and technology spending function collectively as a unified performance framework.

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Keywords: Strategic cost management, Digital transformation, Cost efficiency, Bank performance, Management accounting, Iraqi banks, Panel data

1. Introduction

Financial institutions rival one another based on reputation, geographic reach, risk management, data handling, and expenditure control. Technological modernization reshapes all five areas. Tools like smartphone apps, plastic cards, virtual wallets, POS terminals, streamlined workflows, data intelligence, APIs, and defense systems lower the incremental expense of standard operations and broaden consumer outreach. Yet, accounting

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improvements do not follow automatically. An institution might computerize a flawed workflow, keep redundant human oversight, maintain excess physical branch space, or distribute channel expenses using broad averages that mask hidden cross-subsidies. Consequently, executives must determine not just whether their institution owns digital tools, but how well they oversee the foundational and operational expenses tied to those systems. Strategic cost management (SCM) supplies the managerial accounting framework to address this dilemma. It connects financial data directly to corporate strategy by analyzing cost drivers, business activities, value chains, capacity, quality, client segments, offerings, delivery channels, and market rivals, rather than relying solely on overall budget caps. Structural cost management deals with long-term commitments like software architecture, branch footprints, third-party outsourcing, workflow layout, and IT scaling. Meanwhile, executional cost management focuses on maximizing the utility of locked-in resources through metric tracking, performance comparisons, quality boosts, and workflow streamlining [1], [2]. At the same time, broader evaluations of strategic management accounting note that implementation varies widely and depends heavily on internal firm environments and leadership practices [3], [4], [5]. This dynamic takes on heightened significance within the Iraqi financial sector. Physical cash handling and legacy branch models still hold sway, even as the Central Bank of Iraq pushes forward with modernized payment systems, interbank networks, automation, security protocols, financial inclusion, and electronic services. Digital upgrades formed a core pillar of the 2021-2023 roadmap and persist within the Central Bank's subsequent 2024-2026 strategic agenda [6], [7]. While these shifts promise reduced transaction costs, richer data, wider reach, and better service, they also amplify the necessity of linking tech spending directly to resource usage, operational efficiency, and bottom-line returns. Recent academic literature increasingly views digitization as a complex, multifaceted competence rather than mere ownership of specific software. Xie and Wang [8] build a bank-specific transformation index and link it to financial outcomes in China. Porfirio et al. [9] stress that internal culture and leadership dictate how transformation unfolds, whereas Citterio et al. [10], Ayadi et al. [11], and Shen et al. [12] demonstrate that earnings and efficiency depend on IT productivity, network setups, expense realization, and the depth of transformation. Although these findings highlight the importance of digital readiness, they leave a gap for a clearer management-accounting perspective on how digital insights actually drive cost and capacity choices in developing economies.

This research bridges the gap between strategic cost management and banking digitalization studies. It investigates whether the Strategic Cost Management Index (SCMI) and the Digital Transformation Index (DTI) individually correlate with cost efficiency and financial results, whether the two capabilities reinforce each other conditionally, and whether the Cost-to-Income Ratio (CIR) acts as a statistical mediating channel linking them to profitability. SCM is framed as an organizational ability that turns digital metrics and operational transparency into cost-driver insights, profit clarity, capacity planning, and executive action. The paper makes four distinct contributions. First, it elevates strategic cost management to a central explanatory driver rather than treating it as an afterthought. Second, it introduces a bank-level SCMI tailored to documentary records while carefully separating public disclosures from verified internal routines. Third, it models the interdependent relationship between SCMI and DTI, acknowledging that while digital platforms enhance measurement, SCM dictates how those insights are applied. Fourth, it tests CIR as a statistical transmission mechanism while remaining mindful of the mathematical overlap connecting expense and profitability metrics. Together, these elements expand empirical insights from Iraq while addressing the inherent boundaries of disclosure-derived indices.

2. Literature review and hypothesis development

2.1. Strategic cost management in banking

Strategic cost management (SCM) pushes cost analysis well past mere short-term budget adherence, focusing instead on deliberately shaping cost architectures and resource allocation to reinforce a firm's competitive edge. Academic literature typically categorizes strategic management accounting tools into five areas: costing, planning and control, competitor assessment, customer profitability, and strategic decision support [13], [14].

Prior evaluations indicate that while certain techniques—such as benchmarking, customer analysis, strategic pricing, and specific costing approaches—see widespread use, full implementation of the complete toolkit is less common, particularly in emerging markets [3], [5]. Within the banking sector, relevant cost objects span product lines, distinct customer segments, service channels, workflow processes, physical branches, regulatory obligations, and digital platforms. Activity-based costing (ABC) and time-driven activity-based costing (TDABC) enhance cost traceability by routing resource expenses through specific activities based on practical capacity. Target costing begins with market-dictated pricing or margin targets, working backward to determine allowable cost thresholds. Value-chain analysis uncovers cost-saving and differentiation vectors across customer acquisition, onboarding, transaction handling, lending operations, collections, reporting, and post-sale support. Furthermore, analyzing customer and channel profitability unmasks cross-subsidization patterns that aggregate bank-wide averages often mask. Tools like benchmarking, quality costing, and life-cycle valuation aid in process comparisons, the tracking of prevention and failure expenses, and total-cost-of-ownership evaluations [15], [16]. Higher observed application of SCM should naturally correlate with a lower cost-to-income ratio (CIR) when cost-driver reviews successfully root out non-value-adding tasks, redundant oversight, idle capacity, and expensive delivery paths. Likewise, greater SCM usage should boost return on assets (ROA) and return on equity (ROE) as management shifts resources toward high-yield customers and channels, refines pricing models, and makes smarter sourcing and technological choices. These outcomes stem from purposeful resource orchestration rather than blunt, indiscriminate spending cuts.

H1: Strategic cost management exhibits a negative relationship with the cost-to-income ratio of Iraqi banks; conversely, it correlates positively with overall cost efficiency.

H2a: Strategic cost management is positively linked to return on assets across Iraqi banks.

H2b: Strategic cost management is positively linked to return on equity across Iraqi banks.

2.2. Digital transformation and cost efficiency

Digital transformation encompasses synchronized shifts in technology, operating procedures, service models, data frameworks, workforce competencies, and governance structures. In banking, this spans both customer-facing interfaces and backend infrastructure. The efficiency upside stems from automation, straight-through processing, reduced manual reconciliation, scalable service delivery, and streamlined information flows. Nonetheless, outdated legacy architecture, poor systems integration, steep migration costs, and lingering redundant capacity can delay or erode projected benefits [9], [17], [18].

Consequently, the critical metric is the depth of transformation rather than the mere adoption of isolated technologies. A comprehensive composite index should differentiate between underlying infrastructure and actual usage intensity, service breadth, operational readiness, cybersecurity posture, and payment network integration. A higher digital transformation index (DTI) is expected to drive down the CIR as digital channels substitute for labor-intensive manual tasks, provided banks suitably adjust their staffing, branch footprints, controls, and process ownership to match the evolving channel mix.

H3: Digital transformation shares a negative association with the cost-to-income ratio of Iraqi banks; equivalently, it correlates positively with cost efficiency.

2.3. Digital transformation and bank performance

Beyond cost reduction, digital transformation can enhance profitability by shrinking service delivery expenses, expanding customer reach, generating fee and commission revenue, accelerating product rollouts, optimizing asset utilization, and improving risk intelligence. However, these performance payoffs may materialize non-linearly or with a time lag because initial capital expenditures and migration overhead precede economies of scale. Contemporary empirical banking studies confirm positive average performance links while emphasizing that IT efficiency, network topology, and transformation intensity play decisive moderating roles [8], [10], [11], [12].

H4a: Digital transformation is positively associated with return on assets in Iraqi banks.

H4b: Digital transformation is positively associated with return on equity in Iraqi banks.

2.4. Cost efficiency and bank performance

The CIR measures operating expenditures as a fraction of operating income; lower figures signal that a bank utilizes fewer operational resources to generate each unit of revenue. A depressed CIR should theoretically translate into elevated ROA and ROE, provided service quality, risk management, and revenue-generation capabilities remain stable. Even so, this relationship demands careful interpretation because CIR and profitability metrics share common income-statement variables, meaning a portion of the observed statistical link may stem from accounting mechanics rather than a purely independent operational driver.

H5a: The cost-to-income ratio is negatively associated with return on assets in Iraqi banks.

H5b: The cost-to-income ratio is negatively associated with return on equity in Iraqi banks.

2.5. Complementarity between SCM and digital transformation

SCM and digital conversion are anticipated to function as mutual complements. Digital platforms yield granular telemetry on transaction speeds, channel preferences, exception rates, capacity utilization, customer behaviors, and operational outputs. Meanwhile, SCM provides the cost accounting models, accountability frameworks, profitability lenses, and decision rules required to translate that raw data into actionable strategies. Absent robust costing methodologies, a bank might track digital activity yet remain blind to true channel economics or fail to decommission obsolete capacity. Conversely, without rich digital data, SCM frameworks may default to crude cost-allocation keys and sluggish reporting cycles.

Within the current empirical design, this complementarity is captured via a mean-centered interaction term (SCMI x DTI). A negative interaction coefficient within the CIR specification alongside positive interactions in the ROA and ROE models would indicate that the efficacy of one capability amplifies as the level of the other increases. Because an interaction term alone cannot definitively prove organizational synergy, these conclusions will be corroborated using marginal-effect calculations and confidence intervals in the empirical appendix.

H6a: The SCMI x DTI interaction term is negatively associated with the cost-to-income ratio.

H6b: The SCMI x DTI interaction term is positively associated with both ROA and ROE.

2.6. Mediation and ownership heterogeneity

Both managerial capabilities may influence profitability directly as well as indirectly through CIR mediation. Direct channels encompass pricing strategies, market penetration, service differentiation, and risk-appetite choices. The indirect mechanism captures the statistical pathway running from a capability to CIR, and subsequently from CIR to profitability. This is framed as a mediation-style decomposition rather than a definitive causal claim, given that sequential ignorability cannot be fully established within observational panel data [19]. Furthermore, ownership structures can condition how these practices are implemented, as private and state-owned financial institutions often operate under distinct objectives, decision-making speeds, governance models, and resource constraints.

H7a: The cost-to-income ratio mediates a statistically significant indirect pathway linking strategic cost management to bank profitability.

H7b: The cost-to-income ratio mediates a statistically significant indirect pathway linking digital transformation to bank profitability.

H8: The performance-enhancing associations of SCMI and DTI are more pronounced among private banks than among state-owned institutions.

3. Theoretical framework

3.1. Managing structural and executional expenses

The division between structural and executional factors clarifies why identical technology outlays often yield divergent results. Structural decisions dictate a bank's chosen magnitude, breadth, customer touchpoints, technological stack, operational intricacy, and network topology. Conversely, executional decisions govern labor engagement, workflow standards, throughput levels, offering design, and internal synchronization. A digital overhaul constitutes a structural obligation when it alters foundational platforms and distribution channels; it functions as an executional competency when an institution leverages analytics and workflow transparency to optimize everyday resource expenditure. Consequently, SCMI incorporates indicators reflecting both overarching strategic architecture and day-to-day cost containment [1], [2].

3.2. The resource-based perspective and adaptive competencies

According to the resource-based paradigm, performance disparities stem from assets that are valuable, uncommon, hard to replicate, and properly structured [20]. Hardware and software are commercially available commodities, meaning technology alone lacks scarcity. True differentiation stems from synthesis: information integrity, personnel expertise, workflow restructuring, data protection, financial oversight, and executive governance. Furthermore, dynamic capabilities highlight the ability to detect market shifts, capture opportunities via capital deployment, and continually evolve the asset portfolio alongside shifting technologies and consumer habits [21]. SCM reinforces these mechanisms by measuring financial impacts and tracking whether projected gains materialize.

3.3. Transaction cost and contingency frameworks

Transaction cost economics demonstrates how automated workflows lower expenses related to discovery, validation, fulfillment, oversight, alignment, and administration [22], [23]. SCM highlights these savings and separates genuine efficiencies from mere expense shifting. Meanwhile, contingency theory posits that no single management accounting or digital architecture works best in every scenario. Success relies on alignment across competitive positioning, market volatility, enterprise design, IT infrastructure, and leadership practices. Prior empirical studies in strategic management accounting underscore the significance of this alignment and active managerial involvement [14]. The interaction variable utilized in this research directly captures the empirical fit connecting information technology with expense oversight.

3.4. Comprehensive conceptual architecture

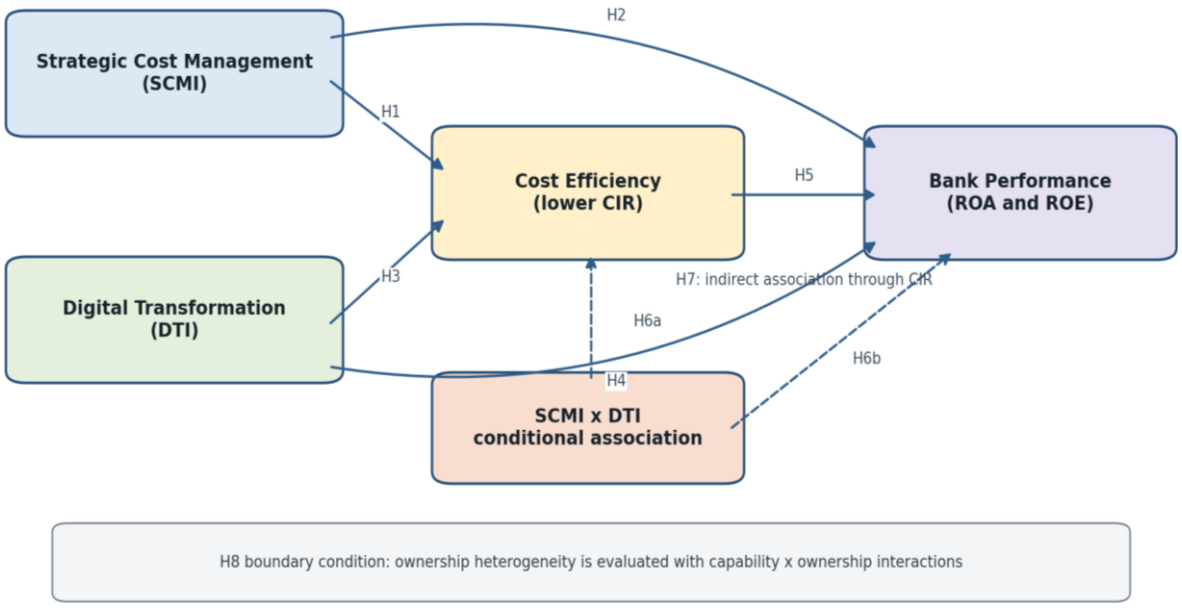


Figure 1. Integrated conceptual framework

This synthesized framework frames SCMI and DTI as mutually supportive organizational strengths. Both connect to the CIR, ROA, and ROE metrics; the CIR acts as a hypothesized statistical transmission mechanism; the SCMI x DTI product captures conditional relationships; and ownership diversity is assessed via capability-ownership interactions. Institution-specific attributes and temporal fixed effects are incorporated to minimize omitted variable bias, recognizing that the observational setup precludes definitive causal claims (Figure 1).

4. Methodology

4.1. Design, scope, and sample selection

This investigation employs an unbalanced panel of bank-year data covering Iraqi commercial institutions—both state-backed and privately held—from 2008 through 2024, gathered from annual reports and comprehensive operational disclosures. Following the removal of institutions lacking necessary financial data for computing return on assets (ROA), return on equity (ROE), or the cost-to-income ratio (CIR), the final dataset comprises 286 observations spread across 22 distinct entities. The analysis operates at the bank-year level, utilizing an unbalanced configuration to incorporate all valid data points organically without imputing figures for missing periods.

Data pertaining to financial metrics originate from published bank reports, official disclosures, and regulatory statistical releases, whereas macro-level indicators come from recognized national and global databases. The digitization index (DTI) is constructed using institution-level data covering digital platforms, transaction volumes, service offerings, technological preparedness, cybersecurity measures, and payment network integration. Meanwhile, the strategic cost management index (SCMI) is derived from annual reports, governance documentation, internal control overviews, and supplementary disclosures addressing budgeting, cost accounting, profitability, performance benchmarking, capacity utilization, and strategic tracking. Regulatory background is informed by Central Bank of Iraq publications [6], [7], though these documents do not replace entity-specific data.

To maintain consistency, entity names and reporting entities are harmonized longitudinally. ROA and ROE are computed utilizing average equity and asset figures whenever beginning-of-year balances are accessible, whereas CIR is defined as operating expenses divided by operating revenues. Where dictated by the statistical framework, continuous financial metrics undergo winsorization at the 1st and 99th percentiles of the pooled distribution. To control for unobserved heterogeneity, the econometric approach incorporates bank fixed effects for time-invariant traits and year fixed effects to capture aggregate macroeconomic shocks [24], [25].

4.2. Quantifying strategic cost management

The SCMI is an index built upon textual disclosures. Individual items are assigned a score of zero for the absence of evidence, one for rudimentary, partial, or pilot implementation, and two for institutionalized application tied to decision-making or performance oversight (shown in Table 1). Resulting scores are subsequently rescaled to a zero-to-one interval, taking care during analysis to differentiate between a lack of reporting and a complete absence of the underlying practice. Rigorous replication demands an independently evaluated subset and a reliability metric like Cohen's kappa [26], accompanied by a detailed coding log. Because this validation output is omitted from the main manuscript, the SCMI should be interpreted provisionally as a disclosure-based metric until the supplementary validation materials are provided (1).

Table 1. Components and coding logic of the Strategic Cost Management Index

Component	Banking application	Observable evidence
Activity-based costing	Costs traced through activities to products, customers, or channels	Activity pools, driver rates, process costs
Time-driven ABC	Resource cost per time unit and practical capacity	Processing time, capacity cost rates, unused capacity

Component	Banking application	Observable evidence
Target costing	Allowable service cost derived from price or margin target	Design-to-cost, target margin, cost gap
Value-chain analysis	Cost analysis across acquisition, onboarding, service, lending, and collection	End-to-end process maps, value-chain redesign
Cost-driver analysis	Structural and executional drivers used in planning and control	Volume, complexity, time, quality, exception drivers
Benchmarking	Internal or external comparison of cost and process performance	Peer, branch, process, or channel benchmarks
Customer profitability	Revenue, risk, and service cost analyzed by segment or customer	Segment contribution, relationship profitability
Channel profitability	Cost and income compared across branch and digital channels	Cost per transaction, channel contribution
Quality and life-cycle costing	Prevention, failure, implementation, operation, and retirement costs considered	Quality-cost reports, total cost of ownership
Capacity management	Supplied and used capacity identified and acted upon	Idle capacity, staffing or branch reconfiguration

Note. Coding scale: 0 = absent; 1 = partial, pilot, or descriptive evidence; 2 = systematic use linked to decisions or performance. SCMI equals the sum of coded items divided by the maximum possible score.

$$SCMI_{it} = (\Sigma_j s_{jit}) / (2J), \quad j = 1, \ldots, 10 \tag{1}$$

4.3. Quantifying digital transformation

The DTI relies on five core pillars: technological infrastructure, extent of digital adoption, digital service offerings, funding and preparedness for digital initiatives, and alignment with national payment infrastructures. Since metrics are expressed in varying units, standardization occurs prior to synthesis (shown in Table 2). The primary model assigns equal weight to each component, whereas entropy and principal-component weightings serve as robustness checks following guidelines from the OECD, European Union, and EC-JRC [27]. To ensure results can be independently replicated, the accompanying materials need to detail every individual metric, its origin, measurement unit, polarity, strategy for handling gaps, scaling timeframe, and final assigned weight. High-level summaries regarding alternate weighting schemes must not replace the disclosure of specific coefficients (2).

Table 2. Dimensions of the Digital Transformation Index

Dimension	Representative indicators	Expected cost mechanism
Infrastructure	ATMs, POS terminals, cards, core platforms, mobile and internet banking	Scalable processing and channel substitution
Usage	Digital transaction volume/value, active digital users, electronic share	Higher fixed-cost utilization and lower unit cost
Services	Mobile banking, e-payments, transfers, e-KYC, digital onboarding	Fewer manual contacts and faster cycle time
Investment and readiness	IT expenditure, upgrades, cybersecurity, staff capability	Reliability, automation, and control
Integration	Connection with clearing, retail payment, settlement, and national systems	Lower coordination and reconciliation cost

Note. Positive indicators use min-max normalization. Higher DTI denotes deeper transformation rather than simple technology possession.

$$X^*_{jit} = (X_{jit} - \min X_j) / (\max X_j - \min X_j); \quad DTI_{it} = \Sigma_j w_j X^*_{jit} \tag{2}$$

4.4. Dependent and control variables

Table 3. Variable definitions and expected signs

Symbol	Variable	Operational definition	Expected sign
CIR	Cost efficiency proxy	Operating expenses / operating income × 100; lower is better	SCMI, DTI: −
ROA	Return on assets	Net profit after tax / average total assets × 100	SCMI, DTI: +
ROE	Return on equity	Net profit after tax / average total equity × 100	SCMI, DTI: +
SIZE	Bank size	Natural logarithm of total assets	+/−
CAP	Capitalization	Total equity / total assets	+
LIQ	Liquidity	Liquid assets / total assets	+/−
LOANG	Loan growth	Annual growth rate of gross loans	+/−
LTD	Loans to deposits	Gross loans / customer deposits	+/−
AGE	Bank age	Years since establishment	+/−
OWN	Ownership	1 = private bank; 0 = state-owned bank	Moderator
INF	Inflation	Annual consumer-price inflation	−
GDPG	Economic growth	Annual real GDP growth	+

Note. CIR is interpreted inversely: a negative coefficient indicates improved cost efficiency. Average assets and equity are preferred where opening balances are available.

Variable definitions and expected signs are shown in Table 3.

4.5. Empirical models

To evaluate how SCMI and DTI relate to CIR, ROA, and ROE conditionally, our primary specifications incorporate both bank and temporal fixed effects. We further introduce an interaction framework by incorporating a mean-centered product term of SCMI and DTI. While this centering procedure leaves overall model fit and interaction estimates untouched, it ensures that individual main effects reflect impacts evaluated at the sample average of the corresponding capability (3), (4).

$$Y_{it} = \alpha + \beta_1 SCMI_{it} + \beta_2 DTI_{it} + \gamma Controls_{it} + \mu_i + \tau_t + \varepsilon_{it} \tag{3}$$

$$Y_{it} = \alpha + \beta_1 SCMI^c_{it} + \beta_2 DTI^c_{it} + \beta_3 (SCMI^c_{it} \times DTI^c_{it}) + \gamma Controls_{it} + \mu_i + \tau_t + \varepsilon_{it} \tag{4}$$

There the dependent variable Y stands for ROA, ROE, or the cost-to-income ratio (CIR). Institution-specific time-constant traits are absorbed by bank effects, broader macroeconomic shocks are controlled via year effects, and unmodeled bank-year fluctuations reside in the disturbance term. Bank-level clustering is applied to the baseline standard errors. A Hausman specification test guides the choice between random and fixed effects, whereas heteroskedasticity, autocorrelation, and cross-sectional correlation are checked using the Modified Wald, Wooldridge, and Pesaran CD diagnostics, respectively. As an additional robustness check, Driscoll-Kraay standard errors are utilized [28], [29]. Given that the dataset is limited to 22 bank clusters, statistical inference ought to be verified via a small-sample method like the wild cluster bootstrap [30].

4.6. Mediation, moderation, and endogeneity

The mediation framework evaluates the pathway from capabilities to CIR, the overall relationship between capabilities and financial returns, and the direct link that remains once CIR is introduced. Indirect effects are derived by multiplying coefficients and tested using bootstrap confidence intervals clustered at the bank level. Because the empirical framework fails to satisfy the sequential ignorability conditions necessary for true causal mediation, these estimates should not be viewed as identified causal mechanisms [19]. Interactions involving SCMI and DTI with ownership (SCMI × OWN and DTI × OWN) test for ownership-based differences. While System GMM and lagged indices are applied to address reverse causality, they are viewed as secondary checks

rather than definitive fixes; any System GMM presentation must disclose instrument tallies, lag restrictions, collapse choices, AR(1) and AR(2) tests, and Hansen J-statistics [31].

4.7. Data quality and reproducibility

Verification and replication rely on four core files: the primary bank-year table, the coding sheets for SCMI items, the weighting and indicator records for DTI, and the corresponding code scripts. While the paper outlines the operational definitions and presents the numerical results from the provided files, the raw records themselves are omitted from the text. These files ought to be uploaded as supplementary journal attachments or stored in an approved archive. Until such a replication package is accessible, the findings can be reviewed but cannot be independently verified using the manuscript alone.

4.8. Measurement validity and disclosure bias

Public reporting forms the basis for SCMI and portions of DTI, introducing two primary validity concerns: silence on a metric might be incorrectly treated as a lack of adoption, and institutions with greater transparency might attain higher index scores simply due to better reporting rather than superior capabilities. Consequently, the findings reflect strictly observable, disclosure-backed competencies. Addressing this validity threat necessitates item-level coding samples, tests of inter-rater reliability, tracking indicator availability across bank-years, and running sensitivity checks against a general disclosure score.

5. Empirical results

5.1. Descriptive statistics

The final estimation sample comprises 286 bank-year observations. On average, ROA is 1.340%, ROE stands at 9.420%, and CIR is 61.350%. The mean values for SCMI and DTI are 0.516 and 0.470, respectively, displaying substantial overall spread. Although these summary metrics indicate adequate dispersion across the key indicators, fixed-effects models rely primarily on within-entity variation; hence, supplemental files should supply the between- and within-group standard deviations along with observation counts per bank (Table 4).

Table 4. Descriptive statistics

Variable	Obs.	Mean	Std. dev.	Min	Max
ROA (%)	286	1.340	1.720	−4.850	6.720
ROE (%)	286	9.420	7.850	−18.600	31.450
CIR (%)	286	61.350	14.280	32.100	94.700
SCMI	286	0.516	0.193	0.100	0.950
DTI	286	0.470	0.210	0.080	0.910
SIZE	286	15.860	1.120	13.240	18.470
CAP	286	0.142	0.061	0.041	0.326
LIQ	286	0.312	0.118	0.084	0.641
LOANG	286	0.087	0.196	−0.382	0.711
LTD	286	0.548	0.214	0.136	1.184

Note. SCMI and DTI range from 0 to 1.

5.2. Relationships and diagnostic checks

There is a positive association between SCMI and DTI ($r = 0.472$), pointing to parallel advancements in digital and accounting proficiencies without crossing standard collinearity limits. Furthermore, both metrics show positive links to ROA and ROE alongside inverse relationships with the CIR. Diagnostic checks indicate a mean VIF of 1.71 alongside a peak value of 2.46, and the Hausman test results point toward fixed-effects specifications. The presence of heteroskedasticity and serial correlation within individual banks necessitates clustered standard errors, with cross-sectional dependence additionally appearing in the CIR regression. Because the dataset contains just 22 clusters, standard clustered p-values ought to be verified using small-cluster bootstrap techniques prior to completion (Table 5 and 6).

Table 5. Correlation matrix for the principal variables

Variable	ROA	ROE	CIR	SCMI	DTI	SIZE
ROA	1.000					
ROE	0.674	1.000				
CIR	−0.518	−0.442	1.000			
SCMI	0.394	0.352	−0.438	1.000		
DTI	0.421	0.384	−0.462	0.472	1.000	
SIZE	0.233	0.198	−0.214	0.291	0.356	1.000

Note. Pearson coefficients are shown. Blank cells denote the upper triangle.

Table 6. Model-selection and diagnostic tests

Test	ROA model	ROE model	CIR model	Inference
Hausman χ^2 (df = 9)	26.14 (p = .002)	22.76 (p = .007)	29.38 (p = .001)	Fixed effects preferred
Modified Wald	p < .001	p < .001	p < .001	Heteroskedasticity present
Wooldridge F	p = .018	p = .026	p = .011	First-order serial correlation
Pesaran CD	p = .084	p = .063	p = .031	Dependence strongest for CIR
Maximum VIF	2.46	2.46	2.46	No serious multicollinearity

Note. Baseline models use bank-clustered standard errors. With 22 clusters, wild-cluster bootstrap p-values should be included in the submission supplement; Driscoll-Kraay estimates should be reported where cross-sectional dependence is detected.

5.3. Fixed-effects findings

The displayed joint fixed-effects regressions align with the hypothesized links, shown in Table 7. SCMI shows a negative link to CIR (beta = -5.621, p < .01) alongside positive links to ROA (beta = 0.588, p < .01) and ROE (beta = 3.314, p < .01). Similarly, DTI demonstrates a negative relation with CIR (beta = -6.784, p < .01) and positive relations with ROA (beta = 0.702, p < .01) and ROE (beta = 3.826, p < .01). Given that both SCMI and DTI undergo mean-centering within the interaction framework, a 0.10 rise in SCMI translates to a CIR reduction of 0.562 percentage points and an ROA increase of 0.059 percentage points when DTI sits at its sample average. A symmetric logic applies to DTI when SCMI is held at its mean. The interaction term yields a negative estimate for CIR and positive ones for profitability metrics. Such directions match the expected conditional dynamic, where the benefit of either capability amplifies as the level of the other rises. Nonetheless, this parameter by itself fails to prove complementarity across the entire data range; the statistical appendix provides the necessary marginal effects and confidence bounds calculated at meaningful levels of SCMI and DTI.

Table 7. Bank and year fixed-effects estimates

Variable	CIR	ROA	ROE
SCMI	−5.621***	0.588***	3.314***
	(1.824)	(0.203)	(1.220)
DTI	−6.784***	0.702***	3.826***
	(1.991)	(0.211)	(1.330)
SCMI × DTI	−3.946**	0.461**	2.710*
	(1.874)	(0.218)	(1.420)
SIZE	−1.427*	0.164**	1.061**
	(0.751)	(0.078)	(0.508)
CAP	−5.904*	1.742**	7.986**
	(3.381)	(0.781)	(3.821)

Variable	CIR	ROA	ROE
LIQ	−2.762	0.474	2.106
	(2.011)	(0.401)	(2.082)
LOANG	−1.693	0.386**	2.512**
	(1.281)	(0.187)	(1.172)
LTD	2.514**	−0.287	−1.318
	(1.196)	(0.231)	(1.291)
INF	0.291**	−0.037*	−0.211*
	(0.142)	(0.021)	(0.123)
GDPG	−0.203*	0.048**	0.259**
	(0.119)	(0.023)	(0.126)
Observations	286	286	286
Banks	22	22	22
Bank / year FE	Yes / Yes	Yes / Yes	Yes / Yes
Within R^2	0.487	0.468	0.431

Note. Bank-clustered robust standard errors are in parentheses. SCMI and DTI are mean-centered before the interaction is formed, so each main coefficient is evaluated at the sample mean of the other index. AGE and the ownership main effect are absorbed by bank fixed effects. * p < .10; ** p < .05; *** p < .01.

5.4. Mediation-style decomposition

When incorporating SCMI, DTI, controls, and fixed effects, CIR shows an inverse relationship with both profitability indicators (Table 8). The computed bootstrap indirect paths reach significance for both SCMI and DTI. Regarding ROA, the aggregate SCMI coefficient drops from 0.812 to 0.541 upon adding CIR, resulting in an indirect effect of 0.271. Similarly, the total DTI coefficient falls from 0.842 to 0.576, yielding an indirect effect of 0.266. Parallel breakdowns are detailed for ROE. Although these findings point toward partial statistical mediation via CIR, causal claims are unwarranted because CIR and profitability metrics overlap in their accounting definitions and the necessary identification conditions cannot be met.

Table 8. Mediation-style decomposition through the cost-to-income ratio

Path	Total effect	Direct effect	Indirect effect	95% bootstrap CI	Decision
SCMI → CIR → ROA	0.812***	0.541**	0.271**	[0.118, 0.438]	Partial mediation
DTI → CIR → ROA	0.842***	0.576***	0.266**	[0.101, 0.427]	Partial mediation
SCMI → CIR → ROE	4.562***	3.106**	1.456**	[0.612, 2.518]	Partial mediation
DTI → CIR → ROE	4.936***	3.402**	1.534**	[0.587, 2.694]	Partial mediation

Note. Indirect associations use 5,000 bank-clustered bootstrap resamples. Confidence intervals excluding zero indicate statistical transmission, not identified causal mediation.

5.5. Diversity in ownership and documented stability

The data regarding ownership dynamics show inverse relationships with the cost-to-income ratio alongside direct positive correlations with return on assets and equity, aligning with more pronounced beneficial outcomes within privately held financial institutions. Prior-period index markers maintain their anticipated polarities. Although System GMM diagnostics indicate successful clearance of both Hansen and second-order autocorrelation checks, the restricted cross-sectional breadth coupled with a modest timeframe renders these figures indicative. Sensitivity checks involving alternative weighting schemes, Driscoll-Kraay adjustments, turbulence-period omissions, and dynamic models ought to appear as comprehensive data matrices within the appendix rather than mere assertions of trend direction (Table 9 and 10).

Table 9. Selected robustness and heterogeneity results

Test / specification	CIR	ROA	ROE	Conclusion
SCMI × Private	−2.814**	0.326**	1.984*	Stronger SCM effect in private banks
DTI × Private	−4.687**	0.612**	3.428**	Stronger digital effect in private banks
Lagged SCMI	−4.906**	0.481**	2.886**	Temporal ordering retained
Lagged DTI	−5.874***	0.603***	3.291**	Temporal ordering retained
System GMM: Hansen p	0.271	0.296	0.318	Instrument set not rejected
System GMM: AR(2) p	0.426	0.403	0.391	No second-order correlation

Note. The table reports only numerical summaries present in the analytical manuscript. Complete coefficient tables, standard errors, instrument counts, lag structure, AR(1), AR(2), and Hansen diagnostics should accompany submission. System GMM is supplementary because N = 22 and T is moderate. * p < .10; ** p < .05; *** p < .01.

5.6. Hypothesis decisions

Table 10. Summary of hypothesis testing

Hypothesis	Tested relationship	Result	Decision
H1	SCMI -> CIR	Negative and significant	Consistent
H2a-H2b	SCMI -> ROA and ROE	Positive and significant	Consistent
H3	DTI -> CIR	Negative and significant	Consistent
H4a-H4b	DTI -> ROA and ROE	Positive and significant	Consistent
H5a-H5b	CIR -> ROA and ROE	Negative and significant	Consistent
H6a-H6b	SCMI x DTI -> efficiency and performance	Expected conditional signs	Consistent
H7a-H7b	Indirect associations through CIR	Significant decomposition	Consistent
H8	Capability x private ownership	Stronger reported associations	Consistent

6. Discussion

The core empirical takeaway indicates that strategic cost management (SCM) and digital transformation operate as interconnected competencies rather than standalone expenditures. Digital platforms offer scalable pathways, transactional transparency, and data processing, whereas SCM dictates cost traceability, driver oversight, workflow redesign, and how channel profitability and capacity steer choices. Consequently, the signs of the SCMI × DTI coefficients make theoretical sense, though the data remains correlational and cannot be interpreted as definitive proof that adoption guarantees superior performance by itself. The inverse relationship between SCMI and the cost-to-income ratio (CIR) aligns with structural and operational perspectives on cost control. Structural methods refine choices around technology scale, outsourcing, branch networks, service blueprints, and platform design, whereas operational tactics minimize idle capacity, exceptions, bottlenecks, and rework. This perspective echoes literature stressing managerial application and organizational alignment over the mere presence of specific tools [3], [5], [14]. Alternatively, a rival hypothesis suggests that institutions with superior reporting mechanisms simply disclose cost strategies and results more thoroughly, highlighting why controlling for overall disclosure rigor is essential.

The findings for DTI mirror evidence that technology upgrades boost banking outcomes when paired with operating-model overhauls [8], [9], [10]. They also match observations that the link between digitalization and efficiency can be non-linear because upfront transformation expenses precede scale efficiencies [11]. The interaction findings supply a management-accounting rationale for this variance: running digital and manual workflows simultaneously can stack up extra costs, whereas capacity data and cost-driver insights help reallocate resources and restructure channels. The mediation-style breakdown functions well as an exploratory mechanism check. It demonstrates that part of the observed link between returns and both SCMI and DTI flows statistically through the CIR, alongside a persistent direct link. Still, because ROE, ROA, and CIR draw from

overlapping income-statement metrics, this channel might partly reflect mechanical accounting effects. Testing these dynamics via SFA, DEA, activity-based expenses, or cost-to-assets metrics would offer a cleaner, more independent evaluation of operational efficiency. The ownership-based interactions imply that change agility and governance shape value realization. Private lenders might benefit from sharper competitive incentives and greater agility in shifting resources, whereas state-backed institutions often possess scale advantages paired with public mandates. Given that government-owned banks likely represent a smaller fraction of the sample compared to private firms, further validation is required, specifically regarding group sample sizes, intra-group dispersion, and sensitivity to outlier institutions, before definitive claims about ownership can be made.

7. Managerial and policy implications

7.1. Integrated cost and digital governance

Financial institutions ought to subject major technology initiatives to unified oversight involving IT, operations, finance, risk management, and management accounting. Every business case should explicitly outline the structural cost choice, anticipated shifts in activity drivers, implementation and lifecycle expenses, capacity slated for release or reallocation, top-line impacts, and associated risks. Post-launch evaluations should assess actual versus forecasted driver volumes rather than merely tracking budget variances.

7.2. Channel and customer profitability

Relying on a broad, bank-wide average cost per account falls short when clients utilize diverse service touchpoints and generate varying exception volumes. Banks need to track channel-specific transaction costs, segment-level service costs, net relationship contribution after accounting for credit and servicing expenses, and the financial dynamics of hybrid users who blend branch visits with digital tools. The goal is not to purge high-cost clientele outright, but rather to leverage solid data to reshape pricing, service models, user education, and channel migration strategies.

7.3. Capacity and process management

Technology investments should tie directly to deliberate capacity choices. Time-Driven Activity-Based Costing (TDABC) can quantify utilized capacity, available capacity, and the financial burden of idle capacity across back-office units and branches. While process-mining tools highlight delays, loops, and exceptions, management accounting must assign financial values to these trends and designate accountability. Financial savings should only be logged when resources are successfully cut, shifted to productive tasks, or harnessed to drive measurable gains in service and risk control.

7.4. Regulatory disclosure

Guided by its 2024–2026 strategic roadmap, the Central Bank of Iraq can foster sector-wide progress by promoting uniform reporting on managerial and digital metrics. Key indicators should encompass digital transaction volume, active digital users, system uptime, security incidents, per-channel transaction costs, processing speeds, exception rates, run-versus-change IT spending, realized gains from major tech projects, and reallocated capacity (Table 11). Reporting frameworks must safeguard data security and business confidentiality while facilitating consistent performance comparisons and optimization [7], [32].

Table 11. Proposed managerial-accounting dashboard for Iraqi banks

Perspective	Core metric	Management question	Decision use
Cost drivers	Cost per transaction; time per activity; exception rate	What consumes resources?	Process redesign and driver control
Capacity	Practical capacity; utilization; unused-capacity cost	Which resources are committed but unused?	Redeploy, resize, or retain strategically
Channels	Branch, ATM, mobile, web, and POS contribution	Which channels create value after full service cost?	Channel mix and migration

Perspective	Core metric	Management question	Decision use
Customers	Risk-adjusted relationship contribution and cost-to-serve	Which service patterns create cross-subsidy?	Pricing, segmentation, and service design
Digital projects	Life-cycle cost; benefits realized; payback; reliability	Did the project change drivers and outcomes?	Portfolio prioritization and review
Quality and risk	Prevention, appraisal, failure, fraud, and remediation cost	Where does poor quality destroy value?	Control investment and error prevention
Performance	CIR, ROA, ROE, fee income, adoption, service time	Are cost, revenue, and customer effects balanced?	Strategic performance evaluation

Note. The dashboard should reconcile operational measures with the general ledger and assign each metric to a responsible decision owner.

8. Conclusions and future trends

The research highlights strategic cost management as a core element when examining the shift toward digital banking in Iraq. Fixed-effects calculations demonstrate that transparency-backed SCMI alongside DTI aligns with reduced cost-to-income ratios along with enhanced return on assets and equity, whereas their interplay points toward a conditional capability dynamic. Part of the observed link to financial returns operates through CIR, and ownership breakdowns point to more pronounced effects within private institutions. The primary takeaway is that technological evolution ought to be managed simultaneously as a cost and value overhaul. Digital metrics gain real economic value only when applied to activity-based costing, workflow redesign, channel margins, capacity planning, quality enhancements, and rigorous post-launch audits. For financial institutions in Iraq, this points to the necessity of a cohesive framework that bridges digital planning, managerial accounting, financial disclosures, risk management, and operational output.

Relying on public financial disclosures might mean internal applications of strategic cost methods are underreported. A lack of public disclosure does not automatically signal a total absence of use, meaning SCMI tracks observable, transparency-backed implementation rather than internal practices. Additionally, because SCMI and portions of DTI draw from identical paperwork, a shared disclosure-intensity effect could artificially boost their statistical correlation. Consequently, granular item data, separate coding processes, consensus metrics, and controls for overall reporting quality remain crucial. Although the cost-to-income ratio functions as a standard efficiency benchmark, it fails to capture technical efficiency, service standards, or risk profiles. Furthermore, its accounting makeup shares elements with profitability metrics, complicating causal mediation claims. Subsequent studies should pair CIR with alternative approaches such as stochastic frontier analysis, data envelopment techniques, asset-based cost metrics, or specific transactional costs including processing expenses for loans, payments, and digital onboarding.

The impacts of digitalization might follow non-linear patterns, as upfront spending typically raises expenses prior to realizing economies of scale. Future investigations ought to examine time lags, tipping points, and U-shaped curves; differentiate operational expenses from change-management outlays; and analyze Islamic versus traditional banks separately due to fundamental structural differences. In addition, statistical tests need to accommodate limited bank clusters, and ownership findings must be vetted for group imbalances and outliers.

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Author contribution

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References

[1] S. W. Anderson and H. C. Dekker, "Strategic cost management in supply chains, part 1: Structural cost management," Accounting Horizons, vol. 23, no. 2, pp. 201–220, 2009. https://doi.org/10.2308/acch.2009.23.2.201.

[2] S. W. Anderson and H. C. Dekker, "Strategic cost management in supply chains, part 2: Executional cost management," Accounting Horizons, vol. 23, no. 3, pp. 289–305, 2009. https://doi.org/10.2308/acch.2009.23.3.289.

[3] K. Langfield-Smith, "Strategic management accounting: How far have we come in 25 years?," Accounting, Auditing & Accountability Journal, vol. 21, no. 2, pp. 204–228, 2008. https://doi.org/10.1108/09513570810854400.

[4] B. Nixon and J. Burns, "The paradox of strategic management accounting," Management Accounting Research, vol. 23, no. 4, pp. 229–244, 2012. https://doi.org/10.1016/j.mar.2012.09.004.

[5] M. M. Rashid, M. M. Ali, and D. M. Hossain, "Strategic management accounting practices: A literature review and opportunity for future research," Asian Journal of Accounting Research, vol. 6, no. 1, pp. 109–132, 2021. https://doi.org/10.1108/AJAR-06-2019-0051.

[6] Central Bank of Iraq, Annual report on the strategic plan 2021–2023. 2021. [Online]. Available: https://cbi.iq/static/uploads/up/file-164862888176320.pdf.

[7] Central Bank of Iraq, Third strategic plan 2024–2026. 2024. [Online]. Available: https://cbi.iq/static/uploads/up/file-171732832262523.pdf.

[8] X. Xie and S. Wang, "Digital transformation of commercial banks in China: Measurement, progress and impact," China Economic Quarterly International, vol. 3, no. 1, pp. 35–45, 2023. https://doi.org/10.1016/j.ceqi.2023.03.002.

[9] J. A. Porfirio, J. A. Felicio, and T. Carrilho, "Factors affecting digital transformation in banking," Journal of Business Research, vol. 171, Art. no. 114393, 2024. https://doi.org/10.1016/j.jbusres.2023.114393.

[10] A. Citterio, T. King, and R. Locatelli, "Is digital transformation profitable for banks? Evidence from Europe," Finance Research Letters, vol. 70, Art. no. 106269, 2024. https://doi.org/10.1016/j.frl.2024.106269.

[11] R. Ayadi, L. Chiaramonte, D. Cucinelli, and M. Migliavacca, "Digitalization and banks' efficiency: Evidence from a European analysis," International Review of Financial Analysis, vol. 97, Art. no. 103837, 2025. https://doi.org/10.1016/j.irfa.2024.103837.

[12] C. Shen, J. Wu, Y. Li, and Q. Chen, "Does digital transformation improve the cost efficiency of commercial banks? Evidence from China," Finance Research Letters, vol. 73, Art. no. 106619, 2025. https://doi.org/10.1016/j.frl.2024.106619.

[13] C. Guilding, K. S. Cravens, and M. Tayles, "An international comparison of strategic management accounting practices," Management Accounting Research, vol. 11, no. 1, pp. 113–135, 2000. https://doi.org/10.1006/mare.1999.0120.

[14] S. Cadez and C. Guilding, “An exploratory investigation of an integrated contingency model of strategic management accounting,” Accounting, Organizations and Society, vol. 33, nos. 7–8, pp. 836–863, 2008. https://doi.org/10.1016/j.aos.2008.01.003.

[15] R. S. Kaplan and R. Cooper, Cost & Effect: Using Integrated Cost Systems to Drive Profitability and Performance. Harvard Business School Press, 1998.

[16] R. S. Kaplan and S. R. Anderson, Time-Driven Activity-Based Costing: A Simpler and More Powerful Path to Higher Profits. Harvard Business School Press, 2007.

[17] X. Vives, “Digital disruption in banking,” Annual Review of Financial Economics, vol. 11, pp. 243–272, 2019. https://doi.org/10.1146/annurev-financial-100719-120854.

[18] F. Kitsios, I. Giatsidis, and M. Kamariotou, “Digital transformation and strategy in the banking sector: Evaluating the acceptance rate of e-services,” Journal of Open Innovation: Technology, Market, and Complexity, vol. 7, no. 3, Art. no. 204, 2021. https://doi.org/10.3390/joitmc7030204.

[19] K. Imai, L. Keele, and T. Tingley, “A general approach to causal mediation analysis,” Psychological Methods, vol. 15, no. 4, pp. 309–334, 2010. https://doi.org/10.1037/a0020761.

[20] J. Barney, “Firm resources and sustained competitive advantage,” Journal of Management, vol. 17, no. 1, pp. 99–120, 1991. https://doi.org/10.1177/014920639101700108.

[21] D. J. Teece, G. Pisano, and A. Shuen, “Dynamic capabilities and strategic management,” *Strategic Management Journal*, vol. 18, no. 7, pp. 509–533, 1997. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7%3C509::AID-SMJ882%3E3.0.CO;2-Z.

[22] R. H. Coase, “The nature of the firm,” Economica, vol. 4, no. 16, pp. 386–405, 1937. https://doi.org/10.1111/j.1468-0335.1937.tb00002.x.

[23] O. E. Williamson, The Economic Institutions of Capitalism. Free Press, 1985.

[24] B. H. Baltagi, Econometric Analysis of Panel Data. 6th ed. Springer, 2021.

[25] J. M. Wooldridge, Econometric Analysis of Cross Section and Panel Data. 2nd ed. MIT Press, 2010.

[26] J. Cohen, “A coefficient of agreement for nominal scales,” Educational and Psychological Measurement, vol. 20, no. 1, pp. 37–46, 1960. https://doi.org/10.1177/001316446002000104.

[27] OECD, European Union, and EC-JRC, *Handbook on Constructing Composite Indicators: Methodology and User Guide*. OECD Publishing, 2008. https://doi.org/10.1787/9789264043466-en.

[28] J. C. Driscoll and A. C. Kraay, “Consistent covariance matrix estimation with spatially dependent panel data,” Review of Economics and Statistics, vol. 80, no. 4, pp. 549–560, 1998. https://doi.org/10.1162/003465398557825.

[29] D. Hoechle, “Robust standard errors for panel regressions with cross-sectional dependence,” The Stata Journal, vol. 7, no. 3, pp. 281–312, 2007. https://doi.org/10.1177/1536867X0700700301.

[30] A. C. Cameron and D. L. Miller, “A practitioner's guide to cluster-robust inference,” Journal of Human Resources, vol. 50, no. 2, pp. 317–372, 2015. https://doi.org/10.3368/jhr.50.2.317.

[31] D. Roodman, “How to do xtabond2: An introduction to difference and system GMM in Stata,” The Stata Journal, vol. 9, no. 1, pp. 86–136, 2009. https://doi.org/10.1177/1536867X0900900106.

[32] S. K. Khaleel, I. R. Hassan, and M. Y. Hmood, “Optimization of fuzzy differential equation-based FARDL models for engineering applications: Comparative analysis of linear and quadratic estimators via parallel Monte Carlo simulations,” *Journal of Mechanics of Continua and Mathematical Sciences*, vol. 21, no. 6, Jun. 2026. https://doi.org/10.26782/jmcms.2026.06.00011.