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Cost Efficiency in the Nicaraguan Banking System: A Stochastic Frontier Approach

Jorge Eduardo Masis*

Universidad Nacional de Ingeniería UNI; jorgemasismartinez@outlook.com; https://orcid.org/0009-0004-8585-1740

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Abstract

Over the 2019-2024 period, the Nicaraguan banking system underwent a period marked by macroeconomic shocks and a significant reconfiguration of financial intermediation, characterized by changes in credit dynamics, liquidity accumulation, and asset composition. This arena raises questions about how banks adjusted their cost structures and the extent to which they operated efficiently throughout this process. This study estimates the cost efficiency of the Nicaraguan banking system using a stochastic cost frontier model with a translog specification under the intermediation approach, with a half-normal inefficiency term, estimated by maximum likelihood. The results suggest that the banking system operated, on average, with a high and stable level of cost efficiency. The observed adjustments in the composition of financial outputs and resource allocation were not associated with systematic deviations from the system's average cost behavior, a strong capacity to adapt operationally to changing macroeconomic conditions.

The views and opinions expressed herein are solely those of the authors and do not necessarily reflect the official positions of the institutions with which they are affiliated.

1. Introduction

Within the economic literature, cost efficiency has become a useful approach for assessing how banking institutions adjust their use of resources in response to changes in the macroeconomic and financial environment, particularly in settings characterized by adverse shocks and heightened uncertainty (Bauer et al., 1998; Berger & DeYoung, 1997).

Under such conditions, adjustments in cost structures reflect not only observable operational decisions, but also the way institutions absorb external disturbances while preserving their relative performance. Empirical evidence suggests that these adjustments are often associated with changes in financial intermediation, asset composition, and macroeconomic conditions, making the evaluation of banking efficiency especially relevant during periods of transition and adjustment (Berger & Humphrey, 1997; Kumbhakar & Lovell, 2003).

These dynamics are particularly relevant in small open economies, where banking systems tend to face tighter structural constraints and a more limited capacity to diversify against external disturbances (Beck et al., 2006; Berger & Humphrey, 1997). In such contexts, macroeconomic shocks tend to translate rapidly into changes in the dynamics of financial intermediation, the composition of bank assets, and the operational decisions of institutions, making adjustments in cost structures more visible (Berger & DeYoung, 1997; Bernanke et al., 1999).

In Nicaragua, the 2019–2024 period was marked by a series of economic and financial shocks that directly affected the functioning of the banking system. These developments were reflected in significant changes in financial intermediation, particularly in a reconfiguration of bank assets characterized by a greater share of investments and liquid assets, together with more moderate credit growth (Torres, 2023). Under these conditions, banks were required to adjust their operations and cost structures in response to a more restrictive macroeconomic environment and greater financial caution (Duarte et al., 2022).

The observed changes in financial intermediation and in the composition of banking system assets raise important questions about how institutions adjusted their cost structures and the degree of efficiency with which they operated during this period of transformation. More specifically, it becomes relevant to assess whether the banking system was able to adapt to this adjustment process without incurring significant efficiency losses, or whether the constraints imposed by the environment translated into higher levels of cost inefficiency.

This study therefore aims to estimate the cost efficiency of the Nicaraguan banking system during the 2019–2024 period. To this end, it applies a stochastic cost frontier approach with a translog specification, allowing for a flexible representation of the relationship between costs, output levels, and the relative prices of banking inputs, while explicitly incorporating an inefficiency component. The estimation is based on panel data and is intended to evaluate the aggregate performance of the system as a whole. This approach is well suited for analyzing adjustments in banking cost structures in a context of changing financial intermediation and unfavorable macroeconomic conditions.

The results indicate that the Nicaraguan banking system operated, on average, with a high level of cost efficiency during 2019–2024, with a mean deviation from the efficient frontier of approximately 7%. This finding suggests that, despite the macroeconomic shocks and the changes in financial intermediation observed during the period, the system was able to adjust its cost structure in a manner consistent with the estimated cost frontier, without incurring substantial efficiency losses.

In addition, the decomposition of the error term reveals that a predominant share of the observed variability in costs is associated with the inefficiency component, supporting the use of the stochastic frontier approach for analyzing cost performance. Robustness checks confirm that these conclusions remain unchanged under alternative distributional assumptions and modifications in sample composition, reinforcing the stability of the estimated efficiency measures and their usefulness as an aggregate benchmark for evaluating banking system performance.

The remainder of this paper is organized into five sections, including this introduction. Section 2 reviews the literature on banking efficiency and national-level studies. Section 3 presents the methodology and data. Section 4 reports the empirical results. Section 5 concludes.

2. Literature Review

2.1 Conceptualization of Efficiency

The earliest analyses of efficiency have their theoretical roots in the contributions of Debreu (1951) and Koopmans (1951), who addressed resource allocation and production from a formal optimization perspective through the development of models that define efficiency as the impossibility of improving one dimension of the production process without affecting others. In his work, Debreu (1951) introduced a coefficient of resource utilization that makes it possible to measure the degree of deviation from an efficient allocation within a competitive environment. Koopmans (1951), in turn, established the conditions under which a productive unit is technically efficient through the analysis of feasible production activities, introducing the notion of technological dominance.

Building on these contributions, Farrell (1957) proposed an empirical measure of efficiency by evaluating the performance of a "productive unit" while jointly considering input use and output generation, defining efficiency as "the success in producing as large as possible an output from a given set of inputs" (p. 254). In doing so, he formalized the so-called "efficient frontier" as the theoretical boundary of optimal performance, identifying units operating below this frontier as exhibiting an observable degree of inefficiency.

From the perspective of production theory, the efficient frontier refers to the set of optimal input combinations that make it possible to attain the maximum feasible level of output. Within this framework, efficiency is understood as the optimal use of available resources given a particular technology (Varian, 2015, p. 366). This leads firms to face the economic problem of profit maximization1, understood as the difference between revenues obtained from output sales and the costs incurred in acquiring inputs within the limits imposed by production technology (Sarmiento & Castellanos, 2008, p.20).

The literature distinguishes three main forms of efficiency that a firm may rationally achieve under an economic objective:[2] technical, allocative, and economic efficiency. The first refers to the ability of a productive unit to obtain the maximum level of output given an input allocation, whereas allocative efficiency evaluates whether those inputs are combined in a way that minimizes cost given their relative prices (Coelli et al., 2005, pp. 2–5). Together, these two dimensions make up what is known as economic efficiency, which involves the optimal choice of input and/or output levels conditional on market prices (Vergara, 2006).

However, although traditional economic models assume that firms behave rationally in order to minimize costs or maximize profits, empirical evidence shows that this behavior does not always materialize in practice. Various studies indicate that observed production decisions and actual cost levels do not necessarily result from fully rational optimization processes, but may instead be affected by factors such as operational errors, organizational rigidities, or uncertainty in the economic environment (Kumbhakar & Lovell, 2003; Resti, 1997). As a result, firms may systematically operate below the efficient frontier even when they face the correct technology and prices.

Against this background, Leibenstein (1978) introduced the concept of X-efficiency, a category intended to capture efficiency losses arising from factors internal to the organization that cannot be explained by technical or allocative failures. His argument suggests that, even when firms operate under the correct technology and prices, they may still incur additional costs due to suboptimal behavior. Because these costs are not directly reflected in the production or cost function, they generate deviations from the efficient frontier. Within the banking industry, several studies have shown that a significant share of observed inefficiency originates precisely from these internal causes rather than from conditions such as market structure or the technology employed (Berger & DeYoung, 1997; Berger & Mester, 1997; Humphrey et al., 1991; Sealey & Lindley, 1977).

In the banking literature, Berger and Mester (1997) classify efficiency in financial institutions into three variants according to the

[1]This objective has its counterpart in cost minimization, a principle that summarizes the underlying logic of efficiency within producer theory (Varian, 2015, p. 395).

[2]That is, profit maximization or cost minimization.

underlying economic criterion and the basis of comparison with the best-practice institution: cost efficiency, measured relative to the cost incurred by the most efficient bank in producing the same output bundle under the same conditions; standard profit efficiency, measured relative to the maximum profit attainable given a particular set of input prices and output levels (and other variables); and alternative profit efficiency, which allows for heterogeneity in the prices faced by each firm while producing the maximum attainable profit, and is useful when some of the assumptions underlying the previous concepts do not hold.

Cost efficiency, in particular, has been preferred in studies seeking to evaluate the internal use of resources from a technological and operational perspective, as it identifies the "best-practice" institution and measures deviations from it as inefficiency. In empirical research, this classification has been widely used to decompose the different factors explaining firm performance in terms of cost minimization in banking institutions (Berger & Humphrey, 1997; Berger et al., 1993).

Methodologically, efficiency measurement has relied on two broad approaches: parametric and non-parametric. Among the latter, Data Envelopment Analysis (DEA), developed by Charnes et al. (1978), stands out as a technique that constructs an efficient frontier from linear combinations of the efficient units in the sample. This approach does not require the specification of a functional form or assumptions about the distribution of the error term. However, because it does not incorporate a random component, any deviation from the frontier is interpreted as inefficiency, which may induce bias when external disturbances, measurement errors, or statistical noise are present in the data (Berger & Humphrey, 1997; Coelli et al., 2005).

By contrast, parametric methods construct the efficient frontier through the estimation of a specific functional form, whether for production or costs (Coelli et al., 2005, p. 211). Unlike non-parametric methods, this approach imposes assumptions about the underlying technology of the production process and uses econometric tools to separate inefficiency from other factors affecting observed performance.

In particular, Stochastic Frontier Analysis (SFA) is frequently used in the banking efficiency literature because of its ability to distinguish statistically between inefficiency and random disturbances (Battese & Coelli, 1995). This approach, introduced independently by Aigner et al. (1977) and Meeusen and van den Broeck (1977), assumes that deviations from the optimal frontier may be due both to random error and to systematic inefficiency. This property is especially valuable in sectors such as finance, which are characterized by heavy regulation, exposure to exogenous shocks, and operational volatility, since it allows inefficiency to be distinguished from random disturbances in firm performance (Coelli et al., 2005, pp. 2–5).

2.2 International Empirical Evidence

The empirical literature on banking efficiency has developed substantially since the formalization of the efficient frontier concept proposed by

Farrell (1957), giving rise to a wide range of methods and metrics for evaluating the relative performance of financial institutions. Within this literature, the SFA approach introduced by Aigner et al. (1977) and Meeusen and van den Broeck (1977) has been widely used to estimate cost frontiers in banking systems, making it possible to explicitly distinguish inefficiency from random disturbances inherent in accounting data.

A central reference is the review conducted by Berger and Humphrey (1997), who examine more than 130 empirical studies covering banking systems in 21 countries and find that cost inefficiency is economically significant in virtually all the contexts analyzed. The authors report that average efficiency estimates typically range between 70% and 90%, although with variation associated with the period under study, the definition of outputs and inputs, and the methodology employed. This finding is reinforced by Resti (1997) and Bauer et al. (1998), who show that efficiency levels and the relative rankings of banks are sensitive to the estimation technique, even when the same data are used.

Berger and Mester (1997) show that cost efficiency is a particularly informative measure of bank performance, as it allows deviations from best-practice behavior to be evaluated without requiring strong assumptions about price behavior or the degree of market power. On this basis, the authors estimate cost frontiers for a broad panel of U.S. banks during the 1990–1995 period, using flexible specifications and comparing alternative assumptions for measuring inefficiency. They find that banks operate, on average, with high levels of cost efficiency, and that these results remain relatively robust to changes in functional specification and estimation method.

In terms of functional form, the empirical evidence has generally favored, particularly the translog form, to represent banking production technology (Triunfo, 1997). This specification has been employed in empirical studies that estimate stochastic cost frontiers across different institutional settings. For example, Altunbas et al. (2000) apply a translog cost function to European banks and find gradual improvements in efficiency asso- ciated with processes of financial integration. Similarly, Fries and Taci (2005) show that, in transition economies, translog cost frontiers adequately capture changes in efficiency arising from institutional reforms and the entry of foreign capital.

In Latin America, the empirical evidence also supports the use of stochastic cost frontiers. Studies such as Carvallo and Kasman (2005) for Latin American banks and Sensarma (2006) for emerging economies report efficiency levels comparable to those observed in other regions, although strongly conditioned by macroeconomic stability and the regulatory framework. These studies typically employ translog cost functions and half-normal or truncated-normal distributions for the inefficiency term, finding that aggregate results are relatively robust to the choice of distributional assumption (Kaparakis et al., 1994; Kwan & Eisenbeis, 1995).

In this regard, Greene (2005) shows that efficiency estimates obtained from stochastic frontier models may differ substantially at the individual level when assumptions about heterogeneity and error structure are modified, leading to unstable rankings across institutions. However, the author documents that aggregate measures, such as the mean efficiency of the system, tend to exhibit greater relative stability across specifications, even when dispersion and the identification of individual inefficiency vary considerably. This finding highlights the need to interpret individual comparisons with caution in finite samples and underscores the usefulness of average indicators when the analysis is conducted at the systemic level.

The empirical evidence for European banking systems supports these conclusions. Studies based on parametric stochastic frontiers show that, although individual efficiency estimates and relative rankings across institutions are sensitive to model specification, aggregate measures display greater stability. For example, Weill (2004), in estimating cost frontiers for banks in different European countries, finds that individual efficiency estimates are volatile, whereas average efficiency levels at the level of national banking systems are consistent and comparable over time.

Similarly, Casu and Girardone (2006) document that adjustment and transformation processes in European banking are reflected mainly in changes in the sector's average efficiency rather than in persistent patterns at the level of individual institutions. Additional evidence is provided by Lozano-Vivas and Pasiouras (2010), who show that, once the macroeconomic and regulatory environment is controlled for, conclusions about banking efficiency are more robust at the aggregate level than in bank-by-bank comparisons.

For small and concentrated banking systems, the measurement of average efficiency at the system level constitutes a more robust analytical tool for sectoral diagnosis than individual comparisons. Although the efficiency estimates of individual institutions may be highly sensitive to model specification and the treatment of unobserved heterogeneity, leading to unstable rankings, aggregate measures or system averages exhibit greater stability across different methodologies and specifications (Greene, 2005). This aggregate approach is particularly relevant in small economies, as it makes it possible to isolate the structural behavior of the sector in response to external shocks and regulatory changes, mitigating the idiosyncratic noise of individual institutions and facilitating the identification of industry performance (Díaz, 2009).

2.3 National Evidence and the Structure of the Banking System

The national literature on the Nicaraguan banking system has emphasized the role of financial intermediation as a mechanism for channeling resources between agents with surplus funds and those with financing needs. Within this framework, existing studies have characterized the functioning of the system through analyses of intermediation margins, market structure, and interest-rate adjustment mechanisms, providing evidence on how banks respond to regulatory and macroeconomic conditions. One important strand of research has focused on the determinants of the financial margin. In particular, Cárdenas and Mendieta (2011) and Clevy and Díaz (2005) find that administrative costs, market concentration, and regulatory requirements have a significant effect on margins. These results suggest that banking margins reflect not only risk and market conditions, but also operational and structural factors that shape price formation and banks' cost pass-through capacity.

Regarding the structure of the system, Clevy (2015) documents that the high concentration of the deposit marketlimits the responsiveness of deposit rates to changes in their determinants. This finding is consistent with the view that competitive structure may affect the degree of flexibility of the system and, by extension, the incentives to improve operational performance and contain costs over time.

Complementing this evidence, Rocha (2023) evaluates the degree of competition in the Nicaraguan banking system using the Panzar and Rosse approach and reports evidence consistent with an "oligopolistic" structure. The study also shows that macroeconomic stability and market contestability are important determinants of the system's competitive behavior. This evidence is relevant for efficiency analysis insofar as the degree of competition may shape incentives for managerial discipline and, therefore, the scope for operating with cost slack.

Another branch of the national literature examines the link between financial conditions and real economic performance. In this line of research, Mendieta (2016) constructs an Index of Financial Intermediation Conditions (IFIC) based on information on liquidity, credit risk, and interest rates, and documents that an easing of these conditions is associated with stronger economic activity. Further evidence supports this argument and shows that financial conditions operate as a channel of macroeconomic transmission, with effects that tend to intensify during episodes of weak growth (Duarte et al., 2022). Taken together, these findings reinforce the relevance of interpreting banking system performance, and particularly its operational and cost adjustment, in light of the broader macro-financial environment.

In sum, the national literature suggests that the performance of the Nicaraguan banking system is shaped by structural factors (concentration and competition), operational factors (administrative costs and margin formation), and macrofinancial conditions (intermediation conditions and transmission to real activity). This body of evidence suggests that episodes of adjustment and reconfiguration in financial intermediation modify not only quantities and portfolio composition, but also the incentives and constraints under which cost structures are determined. From this perspective, an assessment of cost efficiency at the system level provides a natural complement to existing evidence by synthesizing aggregate performance and its recent evolution.

2.4 Recent Performance of the Banking System

During the 2019–2024 period, the dynamics of financial intermediation were shaped by an adjustment process involving weaker credit growth and a greater allocation of resources to financial investments, in a context of high liquidity and weaker credit growth following the shocks that began in 2018 (BCN, 2023, pp. 138–144). This environment led to a reconfiguration of bank assets, with investment instruments gaining importance relative to the loan portfolio.

In 2019, the banking system deepened the adjustment process that had begun after the shocks observed since 2018, with a contraction in credit intermediation and a more conservative allocation of resources. In particular, the loan portfolio continued to decline, while the relative weight of investments and liquid assets increased, reflecting a strategy of liquidity preservation and lower exposure to risk (BCN, 2019, pp. 129–135). This shift in the output mix anticipated important changes in the operational structure and, therefore, in the system's cost dynamics.

During 2020, the extraordinary conditions associated with the pandemic reinforced the system's precautionary behavior, consolidating a pattern of high liquidity and subdued credit activity. Deposits showed relative strengthening, while the loan portfolio remained contained, deepening the shift toward investments. At the same time, loan quality came under pressure, in line with an adverse macroeconomic environment (BCN, 2020, pp. 152–157). This type of configuration tends to alter the relationship between costs and outputs by favoring activities that are less operationally intensive over traditional intermediation.

In 2021, the system began to show signs of normalization, with a gradual recovery in banking intermediation. The loan portfolio resumed growth and asset quality improved, while liquidity remained ample, allowing banks to sustain investments along side the rebound in credit. This turning point reflected a transition from a predominantly defensive stance toward a more balanced structure, with direct implications for cost performance, given that the return of credit as the central output typically requires greater efforts in origination, monitoring, and risk management.

By the end of 2022, the banking system was showing signs of gradual recovery, reflected in a rebound in both the loan portfolio and deposits, together with a decline in non-performing and at-risk loan indicators. This behavior pointed to a partial reversal of the conservative approach observed in previous years, while adequate levels of liquidity and solvency were maintained (BCN, 2022, pp. 143–164). The evolution of these indicators reflected a progressive reactivation of traditional banking intermediation.

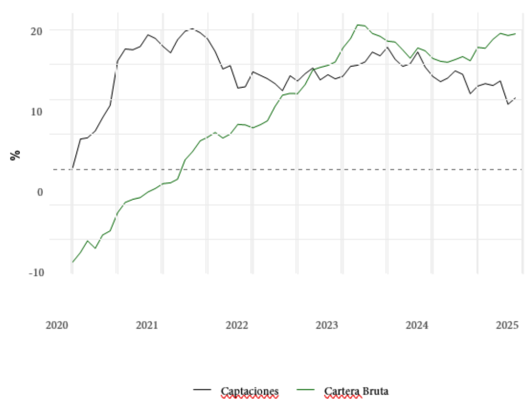
During 2023, the financial system consolidated a more active role in the economy, recording double digit year-on-year loan growth, driven by improved macroeconomic conditions and stronger deposit mobilization. Credit expansion was concentrated in consumption, trade, and productive activities, while loan quality remained at adequate levels. This performance allowed for a gradual reduction in the system's relative exposure to financial investments without compromising its overall soundness (BCN, 2023, p. 138).

Figure 1 illustrates these developments through the year-on-year evolution of deposits and gross loan portfolio, as well as the investment to-assets ratio and the behavior of at-risk loans. Taken together, the indicators show a transition from a structure characterized by high liquidity and lower credit placement toward a more balanced configuration, with a gradual recovery in lending and improvements in asset quality.

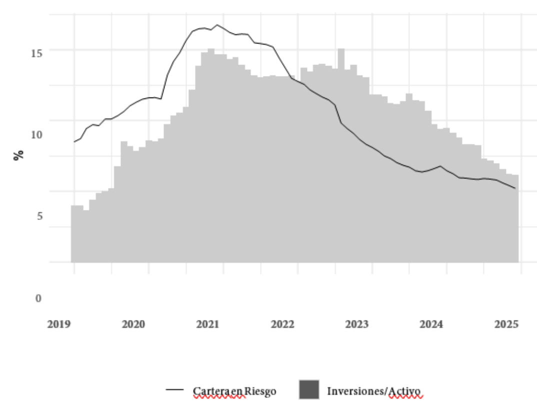
For 2024, performance indicators reflected stability and the consolidation of the adjustment process. Credit regained prominence within the asset structure, accounting for 62.0% of total assets, compared with 56.6% in 2019. By contrast, the share of investments declined 16.3%, a level close to that observed before the adjustment period and significantly below the peak reached in 2022 (BCN, 2024, pp. 134–151).

This asset reconfiguration was accompanied by further improvements in loan quality and

Figure 1: Financial Performance Indicators of the Banking System



(a) Year-on-Year Change (%): Deposits and Gross Loan Portfolio



(b) Evolution of Investments-to-Assets and Loans at Risk (%)

Source: Source: Authors' estimates based on SIBOIF data.

in the system's overall profitability, reflecting a normalization of financial intermediation. Recent developments in the Nicaraguan banking system therefore reveal important operational adjustments in the output mix and in resource use, providing the empirical setting in which cost performance is analyzed over the study period.

3. Methodology and Data

3.1 Stochastic Frontier Model

According to Coelli et al. (2005), if firms pursue the objective of cost minimization and data on observable costs are available, it is possible to estimate the economic characteristics of production technology, as well as efficiency, through the estimation of a cost frontier:

$$c_i \geq c(w_{1i}, w_{2i}, \ldots, w_{Ni}, y_{1i}, y_{2i}, \ldots, y_{Mi}) \quad (1)$$

where *ci* denotes the observed costs of bank *i*, *wi* is the *n-th* price of the inputs used, *yi* is the *m-th* output, and *c(.)* is a nondecreasing, linearly homogeneous, and concave functional form in input prices. Thus, function (1) represents the minimum cost of producing $y_{1it}, y_{2it}, \ldots, y_{Mit}$, when facing input prices $w_{1it}, w_{2it}, \ldots, w_{Nit}$. Following the stochastic frontier approach independently proposed by Aigner et al. (1977) and Meeusen and van den Broeck (1977), the cost function is specified as:

$$c_{it} = x_{it}\beta + \varepsilon_{it} \quad (2)$$

where x_{it} is a $k \times 1$ vector of input prices and outputs, or transformations thereof, for the *i*-th firm, and β is a vector of unknown parameters associated with the structure of the efficient frontier. Deviations from the frontier are represented by the error term (ε_{it}), which is in turn composed of two elements:

$$\varepsilon_{it} = v_{it} + u_{it} \quad (3)$$

The first term, v_{it}, represents a classical error component capturing external disturbances beyond the control of the institution, such as economic fluctuations, random events, or statistical imprecision. The second term, u_{it} corresponds to a non-negative component reflecting inefficiency, that is, the distance between observed costs, which are under the bank's control, and the efficient cost frontier. This term is associated with ineffective managerial practices or suboptimal use of internal resources. Identifying and estimating both components requires adopting specific assumptions about their distributions.

Based on the general specification of the stochastic cost frontier, this study focuses on estimating the average efficiency of the Nicaraguan banking system using a translog cost function under the assumption that the inefficiency term follows a *half-normal* distribution. This implies that inefficiency is distributed asymmetrically, concentrating around values close to zero and declining progressively as the distance from the efficient frontier increases. This choice is justified by its widespread use in the empirical literature and by its ability to capture systematic deviations from the efficient frontier without imposing additional parametric structures on the behavior of inefficiency.

Following the classical approach of Aigner et al. (1977) and Meeusen and van den Broeck (1977), the terms v_{it} and u_{it} are assumed to be independent and distributed as $v_{it} \sim N(0, \sigma_v^2)$ and $u_{it} \sim \left|N\left(0, \sigma_u^2\right)\right|$, respectively. Under these assumptions, the total variability of the composite error term in (3) can be expressed as the sum of the variances of both components:

$$\sigma^2 = \sigma_v^2 + \sigma_u^2 \quad (4)$$

Equation (4) defines the total variance of the residual as the overall dispersion of deviations from the cost frontier. This parameterization makes it possible to rewrite the model in terms of a scalar measure of total variability and a relative measure capturing the contribution of inefficiency. From this expression, Aigner et al. (1977) introduce the parameter:

$$\gamma = \sigma_u^2 / \sigma^2 \qquad (5)$$

which measures the proportion of variance attributable to inefficiency and is bounded within the interval [0,1], thereby summarizing in a parsimonious way the relative importance of systematic deviations as compared with statistical noise. In the limit as γ approaches zero, the model converges to a conventional cost specification with a normal error term, whereas values close to one indicate that inefficiency is the dominant component of observed deviations from the efficient frontier.

Because, in a cost frontier, the inefficiency term u_{it} increases observed costs above the efficient minimum, cost efficiency is defined as a decreasing function of u_{it}. Accordingly, the probabilistic structure of the model makes it possible not only to estimate the efficient frontier, but also to recover aggregate measures of banking system efficiency from the estimated parameters[3].

Thus, cost inefficiency for institution *i* in period *t* may be defined as:

$$\frac{c_{it}}{exp\ (x_{it}\beta + v_{it})} = exp\ (u_{it}) \quad (6)$$

Under the stochastic frontier framework, cost efficiency in (6) is measured as the ratio between estimated minimum cost and observed cost. This indicator makes it possible to assess how close an institution is to operating under best-practice conditions, represented by the efficient frontier estimated from the performance of the most efficient bank in the sample.

Since the database used to estimate the frontier has a longitudinal structure, with observations for multiple entities over time, the model is formulated in terms of the indices *i* and *t*. However, the cost frontier is estimated under a pooled-data approach, in which each entity-period observation is treated as an independent realization of the data-generating process. Accordingly, the temporal dynamics of inefficiency and persistent unobserved heterogeneity at the entity level are not modeled

[3] The structural parameters of the cost frontier, as well as the variance parameters σ2 and γ, are estimated by Maximum Likelihood. The corresponding likelihood function is derived from the implied joint distribution of the composite error term under the normal and half-normal assumptions, as formally developed in Aigner et al. (1977) and later systematized in Coelli et al. (2005).

explicitly, thereby maintaining a cross-sectional stochastic frontier specification applied to repeated observations over time.

It is important to clarify that the parameters associated with macroeconomic shifters and with the inefficiency component describe associations within the framework of the estimated frontier and should not be interpreted as causal effects. The coefficients are therefore reported for their usefulness in characterizing empirical regularities consistent with relative cost performance, rather than for identifying structural mechanisms of causality.

This delimitation reflects the observational nature of the data and the pooled estimation approach, under which unobserved differences across entities may persist and affect both cost structures and performance simultaneously. Likewise, endogeneity arising from simultaneity among production decisions, implicit input prices, balance-sheet composition, and macro-financial conditions, as well as from omitted factors correlated with these variables, cannot be ruled out. For this reason, the interpretation of the shifters and the inefficiency equation remains descriptive.

To assess the robustness of the estimated efficiency measure, complementary exercises are implemented considering alternative distributional assumptions for the inefficiency term, specifically the exponential and gamma distributions, as well as a sample-based contrast that excludes the institution with the largest asset size. This makes it possible to examine the sensitivity of average efficiency and the relative ranking of institutions to changes in the assumptions imposed on the unobserved component and in sample composition.

From a methodological perspective, these exercises make it possible to evaluate the sensitivity of the efficiency measure to alternative assumptions about the unobserved component and to changes in sample composition. Comparing alternative distributions provides a systematic assessment of the extent to which the estimates depend on the assumed functional form for inefficiency, while excluding the largest institution introduces an influence test to examine the robustness of both the aggregate indicator and the relative ranking. Taken together, these checks complement the baseline estimation and provide an additional criterion of internal consistency within the descriptive approach adopted in the study.

3.2 Data and Variables

In efficiency studies in the banking industry, the choice of functional form is conditioned by the theoretical assumptions underlying the econometric methodology employed. Within the framework of the microeconomic theory of production, cost behavior can be modeled through the dual approach by means of cost functions. This link is grounded in Shephard's lemma, which allows the cost function to be derived from the corresponding production function, provided that firms minimize costs given input prices (Coelli et al., 2005, pp. 21–26).

In this context, Diewert (1982) notes that the cost function encapsulates the same technological information as the production function, as long as firms are assumed to minimize costs given input prices. Under this assumption, the specification of a cost function makes it possible to characterize production technology and to formulate empirical efficiency models using accounting information on costs and prices.

Specifying the cost function for banking institutions requires a precise definition of the outputs produced and the resources used. In this regard, the financial intermediation approach proposed by Sealey and Lindley (1977) considers banks as institutions that transform resources such as labor, physical capital and borrowed funds, particularly public deposits, into financial outputs such as loans and investments[4]. This approach has been widely adopted in the literature, making it possible to model banking operations by treating deposits as inputs, insofar as they represent a financial cost that banks must incur in order to obtain funds that are subsequently allocated to profitable activities.

Consistent with this conceptual framework, a translog specification is adopted to estimate the cost function of the national banking system under the traditional financial intermediation approach. As a flexible second-order specification, the translog function[5] relaxes the restrictions imposed by the Cobb–Douglas form, allowing for variable substitution elasticities and non-constant returns to scale. This functional form has been widely used in the empirical literature on banking efficiency[6] because of its ability to capture technological relationships without imposing rigid structures, while also adequately reflecting the multiproduct nature of banking institutions (Triunfo, 1997).

In the empirical application of the model, total costs *(c)* are specified as the sum of financial costs and administrative expenses. Financial outputs are defined as the loan portfolio measured at amortized cost (y_1) and investments (y_2). Three input price proxies are included: the cost of the core deposit base (w_1), the cost of physical capital (w_2), and the cost of labor (w_3). Following the empirical literature, equity is included as a fixed input *(z)*, given its structural nature and its limited capacity for adjustment in the short run.[7] Likewise, a time trend variable *(t)* is incorporated to capture the effect of technological change on efficiency in resource use, which may reflect systematic

[4]An alternative perspective to the intermediation approach is the production approach, which considers banks as "producing" deposits and loans using physical and human resources, thereby treating these financial services as final outputs. However, this perspective has been questioned for ignoring the bank's essential role as a transformer of liabilities into assets and as a channel through which savings are allocated to credit (Sealey & Lindley, 1977).

[5]The function introduced by Christensen et al. (1973) is regarded as one of the most common forms used in efficiency analysis because it satisfies the properties of flexibility, linearity in parameters, regularity, and parsimony (Coelli, 1996, p. 211). For banking structures, Triunfo (1997) highlights the advantages of the translog specification for the analysis of banking firm costs, as it satisfies the conditions of homogeneity, symmetry, monotonicity, convexity, and homotheticity.

[6] See Berger and Humphrey (1997) and Berger and Mester (1997).

[7]Berger and Mester (1997) emphasize the stabilizing role of equity in relation to risk, while Díaz (2009) argues that its inclusion avoids bias in the measurement of efficiency by reflecting differences in banks' risk appetite and funding structures. Thus, equity acts as a "buffer" against insolvency, and its treatment as a fixed input allows its effect on costs to be captured more realistically.

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shifts in the cost frontier over time that are not explained by variations in inputs or outputs[8].

In addition, macroeconomic variables are incorporated as controls in the cost function in order to capture common changes in the operating environment that may affect the cost level of the banking system as a whole. These variables are included as common shifts of the frontier and are not interpreted as structural determinants of inefficiency, but rather as adjustments that allow the unobserved component associated with technical inefficiency to be isolated more precisely.

To improve the numerical stability of the estimation and avoid identification problems associated with collinearity and scale, the variables included in the cost function are expressed as deviations from their sample means. This transformation does not alter the economic properties of the *translog* function, but it contributes to obtaining well-defined estimates of the parameters and the variance components of the model. For the estimation of the stochastic cost function, monthly financial information[9] was collected for the six most representative banks[10] in the National Banking System (NBS) for the period from January 2019 to December 2024, using balance sheet data, income statements, and financial indicators published in the statistical compendium of the Superintendency of Banks and Other Financial Institutions (SIBOIF). With regard to data treatment, the intertemporal comparability of monetary variables was ensured by deflating all amounts corresponding to costs, outputs, and inputs using the Consumer Price Index (CPI) with 2006 as the base year. In addition, during the data-cleaning process, observations were identified that presented values inconsistent with the theoretical assumptions of the model, such as negative values in cost variables or outliers of unusual magnitude.

These observations were excluded from the analysis in order to preserve the functional coherence of the specification and avoid distortions in the estimation of the cost frontier.

Accordingly, the specification of the cost function under the banking intermediation approach can be expressed as:

[8]According to Coelli et al. (1996, p. 213), the inclusion of a time trend in the translog form makes it possible to identify increases or decreases in technological change over time through the incorporation of a quadratic term, so that the effect is defined as: $\frac{\partial \ln(c)}{\partial t} = \tau_1 + 2\tau_2 t$

[9]This procedure is supported the approach proposed by Sealey and Lindley (1977), who argue that banking cost functions can be constructed from accounting data derived from the financial statements of banking institutions. 10At the end of the study period, the selected banks accounted for 99% of total deposits. In order to maintain a homogeneous time structure, a seventh bank was excluded because it began operations after the initial date of the study. Accordingly, the possibility of selection bias is acknowledged, since its performance may differ from the system average, thereby affecting the estimate of average unweighted efficiency.

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$$ln\left(\frac{c}{zw_3}\right) = \alpha_0 + \sum_{k=1}^{2}\alpha_k ln\left(\frac{y_k}{z}\right) + \sum_{i=1}^{2}\beta_i ln\left(\frac{w_i}{w_3}\right) + \gamma_1 ln\, z + \gamma_2 (ln\, z)^2$$
$$+\frac{1}{2}\sum_{k=1}^{2}\sum_{m=1}^{2}\alpha_{km} ln\left(\frac{y_k}{z}\right) ln\left(\frac{y_m}{z}\right) + \frac{1}{2}\sum_{i=1}^{2}\sum_{j=1}^{2}\beta_{ij} ln\left(\frac{w_i}{w_3}\right) ln\left(\frac{w_j}{w_3}\right)$$
$$+\sum_{k=1}^{2}\sum_{i=1}^{2}\rho_{ki} ln\left(\frac{y_k}{z}\right) ln\left(\frac{w_i}{w_3}\right) + \sum_{k=1}^{2}\theta_k ln\left(\frac{y_k}{z}\right) ln\, z + \sum_{i=1}^{2}\phi_i ln\left(\frac{w_i}{w_3}\right) ln\, z$$
$$+\tau_1 t + \tau_2 t^2 + \delta_1 HHI_t + \delta_2 Cycle_t + \delta_3 CPI_t + v + u$$

Within the framework of duality theory, the specification of the cost function must satisfy a set of theoretical restrictions ensuring consistency with rational economic behavior. Accordingly, the restrictions of homogeneity, symmetry, and linearity are incorporated into the functional form[11]:

$$\sum_{i=1}^{2}\beta_i = 1, \qquad \sum_{i=1}^{2}\beta_{ij} = 0 \quad \forall j, \qquad \sum_{i=1}^{2}\rho_{ki} = 0 \quad \forall k$$
$$\alpha_{km} = \alpha_{mk}, \qquad \beta_{ij} = \beta_{ji}, \qquad \rho_{ki} = \rho_{ik}$$

In order to reduce heteroskedasticity problems and avoid scale bias associated with bank size, both total cost *(c)* and the financial output variables, namely loans (y_1) and investments (y_2), were divided by equity *(z)*. This transformation follows the approach proposed by Berger and Mester (1997), who argue that such scaling yields more stable and comparable estimates across financial institutions of different sizes by expressing the variables relative to their capital base.

In addition, the condition of linear homogeneity in input prices was imposed. This property establishes that a proportional change in all input prices must induce a proportional change in total cost. Accordingly, input prices and total costs were expressed relative to the price (w_3).[12]This transformation preserves the functional relationships without altering the elasticities or the economic information contained in the original variables.

Finally, the symmetry condition was imposed on the second-order coefficients of the function, thereby ensuring that cross-variable interactions are consistent regardless of the order in which they are considered[13].

[11] The imposed restrictions arise from the theoretical framework of duality in production economics formalized by Shephard (1970), who demonstrates that every cost function corresponds to an underlying production function, provided that certain regularity conditions such as homogeneity, symmetry, and convexity are satisfied. See alsoVan Zyl (1986), who discusses in detail the empirical implementation of these restrictions in translog functions.

[12] The proxy used for w_3 is justified in terms of productivity and labor costs: (i) as an indicator of labor productivity, where a higher ratio suggests that each employee is generating more income, which may be associated with lower pressure on labor costs, in contrast to lower ratios that may reflect higher-cost structures; (ii) in terms of employment structure and operational efficiency, so that if two banks have similar structures, the one with higher income per employee may be operating with a more efficient workforce, thereby positively affecting cost efficiency; and (iii) in relation to wages, if wages tend to be relatively homogeneous in the financial sector, then higher income generated per employee may be interpreted as a proxy for lower relative labor cost.

[13] According to Van Zyl (1986), the symmetry restriction responds to microeconomic principles of rational behavior and is mathematically supported by Young's theorem, which establishes that the cross-partial derivatives of a continuously differentiable function must be equal when the arguments are interchanged. Therefore, coefficient symmetry is an implicit structural condition in this type of functional model.

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Because the translog cost function is a flexible second-order functional form, its empirical estimation does not automatically guarantee compliance with the conditions of microeconomic regularity. In particular, the properties of monotonicity and concavity in input prices were verified empirically over the range of sample observations, following standard practice in the applied literature on cost frontiers.

Monotonicity was assessed on the basis of the cost shares associated with each input14, verifying that such shares were non-negative. Concavity in prices, in turn, was examined through analysis of the second-order Hessian matrix of the cost function with respect to relative prices, evaluated at each observation15. The results of these checks are reported in aggregate form, making it possible to assess the economic plausibility of the estimated frontier without imposing additional global restrictions on the functional form.

With respect to the macroeconomic variables, indicators associated with competitive structure, the business cycle, and inflationary pressures are incorporated in order to capture common external conditions that may affect the cost level of the banking system as a whole. In particular, the Herfindahl–Hirschman Index applied to the deposit market is included in levels as a measure of concentration and competitive structure, while the business cycle is proxied by the year-on-year variation in the trend-cycle component of the financial intermediation activity index, and inflationary pressures are captured through the year-on-year variation in the core consumer price index.

These variables are incorporated as common shifts in the cost frontier and are not transformed into deviations from the sample mean, since their purpose is to control for aggregate changes in the macroeconomic environment rather than for individual production decisions by banks.

As a preliminary step before estimating of the stochastic cost frontier, diagnostic tests were applied to evaluate whether the empirical characteristics of the data were compatible with the use of a frontier model as opposed to a conventional ordinary least squares specification. In particular, the skewness of the residuals from the OLS cost model was analyzed using the test proposed by Coelli (1995), which makes it possible to examine whether the error distribution exhibits skewness consistent with the existence of a one-sided component associated with inefficiency. This test is used as a prior descriptive check and is not interpreted as a determining condition for adopting the frontier approach.

In addition, a likelihood-ratio test was used to assess the null hypothesis of no inefficiency, formulated as $\sigma_u^2 = 0$ or, equivalently, $\gamma = 0$. Since this hypothesis imposes a restriction on the boundary of the parameter

14 The condition of monotonicity in prices is evaluated using cost shares, defined as $s_i = \partial \ln c / \partial \ln w_i$, where w_i denotes the price of input i. The cost function satisfies the monotonicity property when these shares are non-negative for each input and observation in the sample, that is, $s_i \geq 0 \; \forall i$.

15The function is considered concave in prices when this matrix is negative semidefinite, which is verified empirically by analyzing the sign of its eigenvalues at each sample observation.

space, statistical inference is conducted using the critical values proposed by Kodde and Palm (1986), which account for the non-standard asymptotic distribution of the likelihood-ratio statistic under this type ofrestriction.

These tests are used as preliminary checks of consistency between the assumptions of the model and the empirical characteristics of the data, and are not interpreted as measures of efficiency or as decisive criteria for model selection. In line with the evidence presented by Coelli (1995), it is recognized that this type of test may have limited power in finite samples, particularly when the contribution of the inefficiency component is small. Consequently, the maximum-likelihood estimation of the cost frontier constitutes the central element for measuring cost efficiency in the present study.

4. Empirical Results

In light of the reconfiguration of financial intermediation described in Section 2.4, the results that follow are interpreted as evidence regarding adjustments in the output mix and resource use without a major deterioration in the cost performance of the Nicaraguan banking system. In particular, the aim is to assess whether the transition from a structure characterized by high liquidity and weaker credit placement toward a gradual recovery in lending was reflected in systematic deviations from the estimated cost frontier for the system as a whole.

The estimation of the baseline stochastic cost frontier model is reported in Table 1. Since all variables included in the cost function are expressed as deviations from their sample means, the estimated coefficients should be interpreted as local marginal effects around the average bank and average period in the sample.

The coefficients associated with financial outputs, namely the loan portfolio measured at amortized cost and investments, are positive and statistically significant. This result indicates that positive deviations in output levels, relative to the sample midpoint, are associated with increases in total costs, holding constant relative input prices and the remaining variables in the model. This relationship is consistent with the microeconomic theory of duality and reflects the local behavior of banking production technology around the representative bank in the system.

This result is consistent with the reconfiguration of intermediation described for 2019–2022, when the greater weight of investments and liquid assets implied an operational structure different from the phase of credit recovery observed in 2023–2024. In particular, the return of credit as the central output tends to require greater efforts in loan origination, monitoring, and risk management, which is reflected in a cost technology that is sensitive to changes in the output mix.

The quadratic terms associated with outputs are also significant, which points to the presence of nonlinearities in the relationship between costs and activity levels. In the context of mean-centered variables, these coefficients capture variations in the curvature of the cost function around the sample midpoint, supporting the use of a flexible translog specification to represent the multiproduct nature of the banking system.

With respect to relative input prices, the estimated coefficients for the cost of the core deposit base and the cost of physical capital, both expressed relative to the labor-cost proxy, are positive and statistically significant. Given the centering of the variables, these parameters indicate that relative increases in input prices, with respect to their average values, generate increases in total costs around the sample midpoint for a given relative level of output. This behavior is consistent with the local monotonicity property of the cost function over the range of observations analyzed.

The temporal dynamics of the cost frontier are characterized by a nonlinear time effect. In particular, the quadratic trend term has a negative and statistically significant coefficient, suggesting that the shift in the cost frontier becomes attenuated over the period analyzed. Given the centering of the variables, this result should be interpreted as a gradual change in the average position of the frontier around the temporal midpoint of the sample rather than as a uniform linear trend.

While costs, outputs, and equity are incorporated as deviations from their sample means, macroeconomic controls are included in levels in order to capture common variation in the operating environment. In this regard, the *Herfindahl–Hirschman* Index applied to the deposit market exhibits a positive and statistically significant coefficient, suggesting that higher levels of concentration are associated with higher aggregate costs within the framework of the estimated frontier.

This result may be interpreted in light of two hypotheses discussed in the literature. Under the efficient-structure hypothesis, greater concentration could reflect the expansion of more efficient institutions, which would tend to be associated with lower unit costs. Under the quiet-life hypothesis, by contrast, a more concentrated environment may reduce competitive pressure and weaken incentives for managerial discipline, thereby widening the scope for operational slack and, consequently, higher costs. The positive sign estimated for the *HHI* is more consistent with the latter mechanism, although within the descriptive scope of this study it should be understood as a specification-dependent association rather than as causal evidence regarding the dominant channel.

That is, the *HHI* is used as a parsimonious indicator of concentration in the deposit market, suitable for characterizing changes in the distribution of market shares across institutions. Its inclusion makes it possible to incorporate the structural dimension of the market without altering the main purpose of the paper, which is to measure aggregate cost efficiency in a robust manner. As an extension, future work may assess whether this estimated association is preserved when using measures more closely related to market power, thereby providing a deeper understanding of the mechanisms linking market structure and cost performance.

Table 1: Estimation of the SFA Model under a Half-Normal Distribution

Panel A. Stochastic frontier (costs)

Parameter	Estimate	Standard error	z	p-value
Intercept	-1.21337	0.14452	-8.396	<0.001
$\ln y_1$	0.86752	0.02795	31.037	<0.001
$\ln y_2$	0.06425	0.00471	13.637	<0.001
$\ln z$	0.00530	0.01420	0.373	0.709
$\ln w_1$	0.24598	0.03334	7.377	<0.001
$\ln w_2$	0.65724	0.02826	23.254	<0.001
$I(0.5*\ln y_1^2)$	1.66511	0.17708	9.403	<0.001
$I(0.5*\ln y_2^2)$	0.05953	0.00538	11.054	<0.001
$I(0.5*\ln z^2)$	-0.31819	0.07008	-4.540	<0.001
$I(0.5*\ln w_1^2)$	-0.55890	0.17615	-3.173	0.002
$I(0.5*\ln w_2^2)$	0.00373	0.20251	0.018	0.985
$I(\ln y1 * \ln y_2)$	0.02577	0.01567	1.644	0.100
$I(\ln y1 * \ln z)$	0.31205	0.04049	7.707	<0.001
$I(\ln y1 * \ln w_1)$	-0.24139	0.12042	-2.005	0.045
$I(\ln y1 * \ln w_2)$	0.39266	0.11932	3.291	<0.001
$I(\ln y2 * \ln z)$	0.00953	0.00809	1.178	0.239
$I(\ln y2 * \ln w_1)$	0.02769	0.01873	1.478	0.139
$I(\ln y2 * \ln w_2$	0.01984	0.02177	0.911	0.362
$I(\ln z * \ln w_1)$	-0.11070	0.06555	-1.689	0.091
$I(\ln z * \ln w_2)$	0.01622	0.06061	0.268	0.789
$I(\ln w1 * \ln w_2)$	0.07290	0.13499	0.540	0.589
t	-0.00007	0.00063	-0.119	0.905
t^2	-0.00008	0.00002	-4.829	<0.001
HHI	1.86124	0.55622	3.346	<0.001
Cycle	-0.00174	0.00125	-1.391	0.164
CPI	0.00049	0.00136	0.359	0.720

Panel B. Variance parameters

Parameter	Estimate
σ^2	0.00740
σ_u^2	0.00710
σ_v^2	0.00030
γ	0.96440

Panel C. Model statistics	
LogLik (ML)	686.21952
N	430
LR test (H0: σ2 = 0, df=1)	36.72040
Skewness test, H0: no inefficiency (z)	2.40196
Skewness test, H0: no inefficiency (p)	0.01631
Mean inefficiency ***E[exp(u)]***	0.06735

Note: Panel B reports point estimates.

Source: Authors' estimates.

By contrast, the business cycle and core inflation are not statistically significant, suggesting that once productive structure, relative prices, and the average position of the frontier are controlled for, these variables do not introduce additional systematic variation in costs around the sample midpoint. Rather, operate as common frontier shifters rather than as structural determinants of inefficiency and not as structural determinants of inefficiency.

Regarding the variance parameters, the estimated value of γ indicates that a predominant share of the variance in the composite error term is attributable to the inefficiency component rather than to random noise. Accordingly, the observed variability in costs around the estimated frontier is explained mainly by systematic deviations from the minimum efficient cost implied by the estimated production technology, rather than by purely random disturbances.

The estimated mean inefficiency of the banking system is approximately 0.067, indicating that, on average, observed costs exceed the minimum efficient level by about 6.7 percent, conditional on production technology, relative input prices, and the macroeconomic environment. This measure represents a multiplicative factor of deviation from the efficient cost frontier and should be interpreted as an aggregate and relative indicator, dependent on the model specification and on the benchmark defined by the estimated frontier.

In substantive terms, this level of average inefficiency suggests that, even under a context of adjustment and asset reconfiguration, the system maintained cost performance close to the best practices implicit in the sample. In that sense, the estimated aggregate efficiency can be interpreted as a useful benchmark for monitoring, in comparative terms, whether future episodes of macro-financial stress translate into deteriorations in operational performance.

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In order to assess the sensitivity of the estimated efficiency measures to the distributional assumptions imposed on the inefficiency term, alternative specifications of the baseline model were estimated under the exponential and gamma distributions, while keeping unchanged the translog functional form, the bank sample, and the set of included variables. This exercise makes it possible to evaluate whether aggregate results and the relative ordering of institutions depend critically on the half-normal assumption adopted in the baseline specification.

Table 2 summarizes the main aggregate parameters associated with the variance decomposition and mean inefficiency, together with measures of ordinal stability for the efficiency ranking. Overall, the results show a high degree of consistency across distributional specifications. In all three cases, the parameter γ takes high values, indicating that most of the variance of the composite error term is systematically attributable to the inefficiency component, regardless of the assumed distribution.

Estimates of mean inefficiency show moderate differences across specifications. Under the *half-normal* distribution, average inefficiency is approximately 0.067, whereas the exponential and gamma specifications yield slightly lower values. This gradual reduction in mean inefficiency is consistent with the known properties of these alternative distributions, which tend to assign greater probability mass to values close to zero. Nevertheless, the magnitudes remain within a comparable range, suggesting that aggregate efficiency in the

Table 2: Distributional Robustness: Aggregate Parameters and Ranking Stability

Panel B. Variance parameters and efficiency	**Half-Normal**	**Exponential**	**Gamma**
σ^2	0.00739	0.00369	0.01248
σ_u^2	0.00713	0.00358	0.01231
σ_v^2	0.00026	0.00012	0.00017
γ	0.96436	0.96852	0.98655
Mean inefficiency E[exp(u)]	0.06735	0.05982	0.04947
Panel C. Efficiency ranking stability	–	0.829	0.829
	-	0.058	0.058

Note: Spearman’s correlation evaluates the ordinal stability of the efficiency ranking relative to the baseline Half-Normal model. Given the number of institutions included in the sample (six banks), formal tests have limited statistical power, so interpretation focuses on the magnitude of the correlation coefficient. Under the Gamma specification, some standard errors may not be fully identified; therefore, this specification is used primarily as a complementary robustness check for aggregate parameters and rankings.

Source: Authors’ estimates.

banking system is not substantially altered by the choice of distributional assumption.

In terms of ordinal stability, the Spearman correlation between the efficiency rankings derived from the exponential and gamma specifications and that of the baseline half-normal model is high. This result indicates that the relative ordering of banks is broadly preserved when the distributional assumptions imposed on the inefficiency term are modified. Given the number of institutions included in the sample, formal tests have limited statistical power; accordingly, interpretation focuses on the magnitude of the correlation coefficients rather than on their pointwise significance.

Taken together, these results suggest that the main conclusions of the baseline model in terms of average efficiency and relative institutional performance are robust to alternative distributional assumptions for the inefficiency term. The half-normal specification adopted in the main analysis may therefore be regarded as an adequate and parsimonious representation of the inefficiency-generating process in the Nicaraguan banking system, without the results depending critically on that particular choice.

Table 3: Sample Robustness: Excluding the Dominant Bank

	Baseline Model	Without Dominant Bank
Number of banks	6	5
Observations (N)	430	358
σ_u^2	0.00713	0.00633
σ_v^2	0.00026	0.00043
σ^2	0.00739	0.00676
γ	0.96436	0.93670
LogLik (ML)	686.21952	571.00032
LR test of ineff. $(H0{:}\sigma_u^2 = 0)$	36.72040	21.44075
Coelli (1995) skewness: z	2.40196	1.05425
Coelli (1995) skewness: *p*	0.016	0.292
Mean inefficiency *E[exp(u)]*	0.06735	0.06347

Note: Institutions are presented in anonymized form. The exclusion corresponds to the largest bank in the system.Both models retain the same functional form, macroeconomic controls, and half-normal assumption for the inefficiency term.

Source: Authors' estimates.

To assess whether the results obtained in the baseline model are disproportionately influenced by the presence of a large institution, an alternative specification was estimated excluding the dominant bank in the system. This exercise makes it possible to examine the sensitivity of aggregate efficiency measures and of the model's variance structure to changes in sample composition, while keeping constant the translog functional form, the macroeconomic controls, and the half-normal assumption for the inefficiency term.

Table 3 presents a comparison between the baseline model and the specification estimated without the dominant institution. As expected, excluding the largest bank reduces the number of observations and the value of the log-likelihood, reflecting the smaller sample size. Nevertheless, the parameters associated with the variance decomposition exhibit qualitatively similar behavior across both specifications. In particular, the parameter γ remains high, although it decreases moderately, indicating that inefficiency continues to explain a predominant share of the total variance of the composite error term even in the absence of the dominant institution.

The estimated mean inefficiency of the banking system declines slightly when the dominant bank is excluded, decreasing from approximately 0.067 to 0.063. This suggests that the presence of the largest institution exerts a moderate upward effect on the average deviation of costs from the efficient frontier, without materially altering its overall magnitude.

With respect to diagnostic tests, the likelihood-ratio test continues to reject the null hypothesis of no inefficiency in both models, which supports the use of the stochastic frontier approach even after excluding the dominant bank. By contrast, the skewness test proposed by Coelli (1995) loses statistical significance in the reduced sample, a result consistent with the lower power of the test in smaller samples and with a slightly smaller aggregate contribution of inefficiency.

From an ordinal perspective, the relative ranking of the remaining institutions shows high stability. Banks' positions in terms of efficiency are largely preserved across both specifications, with only minor changes in point estimates and no substantial alterations in the relative hierarchy. This behavior suggests that the baseline results are not driven by the inclusion of a single institution, but rather reflect consistent patterns of relative performance within the banking system.

Taken together, the sample robustness exercise indicates that the central conclusions of the analysis, both in terms of average efficiency and the relative ranking of institutions, are robust to the exclusion of the dominant bank. The baseline specification may therefore be interpreted as an informative representation of cost performance in the banking system as a whole, without the results depending critically on the presence of a single large institution.

The results of the microeconomic regularity tests for the cost function are presented in Table 4. Overall, the evidence shows that the translog specification broadly satisfies the condition of local concavity in prices, whereas monotonicity is only partially satisfied over the range of observations in the sample.

In the baseline model under the half-normal distribution, local concavity is verified for virtually all observations, with a compliance rate of 99.8% and values of the largest eigenvalue of the Hessian matrix close to zero. Consistent results are obtained under the exponential and gamma specifications, for which concavity holds in 100% of the cases and eigenvalues remain negative, supporting the stability of the curvature of the cost function under alternative distributional assumptions for the inefficiency term.

By contrast, the specification excluding the dominant bank shows a marked reduction in compliance with local concavity in prices. This result indicates that the curvature condition is more sensitive when the sample is restricted and should therefore be interpreted as a sample-sensitivity exercise rather than as an alternative characterization with equal overall validity.

In a translog function, concavity is evaluated locally, observation by observation, from the Hessian matrix with respect to prices, so that compliance depends on the empirical range of relative prices and the output-input combinations supporting the estimation.

When the largest institution is excluded, the remaining sample may reflect a different composition of outputs and prices, or a smaller degree of empirical variation for identifying second-order terms with stability. This is consistent with information limitations in the estimation of cur- vature. From a theoretical perspective, the lower concavity rate implies that, for an important share of observations in the reduced subsample, the estimated function does not fully reproduce the concavity condition required by a cost function consistent with cost minimization. The microeconomic interpretation of that frontier should therefore be treated with caution.

Accordingly, this scenario is reported as evidence of local regularity fragility in the subsample excluding the dominant bank, whereas the main analysis relies on the full specification, which satisfies concavity and shows stability in mean efficiency and in the variance parameters under the sample contrast. This supports the view that the aggregate result does not depend critically on a single institution.

Table 4: Regularity Tests for the Cost Function

Criterion	Half-normal (baseline)	Exponential	Gamma	Without dominant bank
Min. deposit (s1)	-0.2948	-0.0842	0.0595	-0.2628
Min. capital (s2)	0.4540	0.5371	0.5521	0.3672
Min. labor (s3)	-0.2164	-0.2564	-0.2609	-0.0770
Monotonicity (%)	70.0000	54.9000	51.6000	68.8000
s1 ≥ 0(%)	89.8000	99.3000	100.0000	74.0000
s2 ≥ 0(%)	100.0000	100.0000	100.0000	100.0000
s3 ≥ 0(%)	80.2000	55.6000	51.6000	94.9000
Local concav (%)	99.8000	100.0000	100.0000	32.3000
λmax (p95)	-0.0448	-0.0793	-0.0428	0.2705
λmax (max.)	0.0125	-0.0499	-0.0031	0.3962

Note: Monotonicity and concavity rates represent the percentage of observations for which the corresponding condition is satisfied. si denotes the implied share of input i in total cost. λmax corresponds to the largest eigenvalue of the Hessian matrix with respect to prices.

Source: Authors' estimates.

As for monotonicity, the joint condition is satisfied in a substantial, though not complete, proportion of observations, with rates ranging from 51.6% to 70.0% depending on the specification. At the individual level, the share associated with physical capital is non-negative in all cases, whereas the shares linked to deposits and labor present isolated episodes of negativity.

The time-based analysis shows that these violations intensify in the final part of the study pe- riod. In particular, joint monotonicity is verified in 86.2% of the observations during 2019–2021, but declines to 54.0% in 2022–2024, with the violation rate rising from 14.0% to 46.0%. The decomposition by input indicates that this deterioration is concentrated mainly in the residual share (s3), which is consistent with observations in which the sum of the estimated shares for deposits and physical capital exceeds unity, causing the labor share, constructed as a residual, to take negative values.

Given the local nature of these checks and the centering of variables around the sample mean, these deviations should be interpreted as localized irregularities rather than as a global violation of the underlying economic theory. As an additional check, excluding the observations that do not satisfy monotonicity leads only to moderate changes in the average output-cost elasticities, from 0.8675 to 0.8239 for y1 and from 0.0625 to 0.0470 for y2, which supports the qualitative stability of the estimated cost technology.

Taken together, the regularity tests confirm that the estimated cost function is economically plausible over the observed range of the data, particularly with respect to concavity in prices, thereby supporting the use of the stochastic frontier approach for analyzing cost efficiency in the banking system.

5. Conclusions

This study estimated the cost efficiency of the Nicaraguan banking system during 2019–2024 using a stochastic cost frontier model with a translog specification, with the aim of characterizing aggregate system performance in a context of macro-financial adjustment and reconfiguration of financial intermediation. The results indicate high levels of cost efficiency throughout the period, with mean inefficiency close to 6–7 percent.

From a methodological perspective, the choice of a translog cost function is appropriate for characterizing the multiproduct nature of banking and allowing for a flexible representation of nonlinearities, interactions, and substitution patterns among inputs. In particular, this approach helps describe the cost structure of the system as a function of changes in the output mix and in relative prices, providing a coherent basis for interpreting the operational adjustment of the Nicaraguan banking system within the observed empirical range.

In substantive terms, the evidence of high average efficiency is consistent with a system that, during the period analyzed, operated with relatively limited cost inefficiency relative to the estimated frontier. This suggests that the observed adjustments in intermediation and asset composition appear to have taken place primarily through changes in the output mix and the relative use of inputs, rather than through persistent deviations from the best practices implicit in the sample. In this sense, the estimated frontier provides an aggregate benchmark for describing the configuration of the system's cost structure over the observed empirical range.

The robustness checks support the consistency of the central finding. In particular, average efficiency and the relative importance of the inefficiency component remain within comparable ranges under alternative distributional assumptions, and the exercise excluding the dominant institution does not substantially alter the aggregate conclusions, even though local curvature becomes more sensitive under the restricted sample. Regarding regularity, concavity in prices is broadly satisfied in the baseline model, whereas monotonicity is only partially verified and follows a clear temporal pattern concentrated in a subset of observations, without materially affecting average elasticities when those cases are excluded.

Finally, the results should be interpreted within the descriptive scope of the adopted approach. Future research could extend the analysis by incorporating strategies that capture persistent heterogeneity across institutions and the temporal dynamics of inefficiency, as well as by examining the association between concentration and costs using metrics more closely related to market power, in order to move toward a more structural understanding of the mechanisms linking market structure and cost performance.

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7. Appendix

Table 5: List of Variables Used in the Estimation

Classification	Variable	Definition	Operational Proxy
Costs	Total Costs	c	Financial Costs + Administrative Expenses
Financial Output	Loan Portfolio at Amortized Cost	y_1	Investments at Amortized Cost + Net Loan Portfolio
Financial Output	Investments	y_2	Investments at Fair Value through Other Comprehensive Income + Equity Participations
Fixed Input	Equity	z	Own Funds + Net Other Comprehensive Income + Transition Adjustments
Input Price	Price of the Core Deposit Base	w_1	Financial Expenses on Public Obligations / Public Deposits (Quarterly Annualized Rate)
Input Price	Price of Physical Capital	w_2	Administrative Expenses / Assets
Input Price	labor-cost proxy	w_3	Financial Income / Number of Quarterly Employees

Source: Authors' estimates.

Table 6: Cost Frontier Estimation under the Exponential Distribution

Panel A. Stochastic frontier (costs)

Parameter	Estimate	Standard error	z	p-value
Intercept	-1.19020	0.09902	-12.019	<0.001
$\ln y_1$	0.84118	0.02149	39.150	<0.001
$\ln y_2$	0.05877	0.00344	17.087	<0.001
$\ln z$	0.01282	0.01049	1.222	0.222
$\ln w_1$	0.34090	0.02510	13.581	<0.001
$\ln w_2$	0.61974	0.02028	30.555	<0.001
$I(0.5*\ln y_1^2)$	1.28456	0.14514	8.850	<0.001
$I(0.5*\ln y_2^2)$	0.04685	0.00462	10.137	<0.001
$I(0.5*\ln z^2)$	-0.12455	0.05309	-2.346	0.019
$I(0.5*\ln w_1^2)$	-0.38735	0.14936	-2.593	0.010
$I(0.5*\ln w_2^2)$	-0.05448	0.15596	-0.349	0.727
$I(\ln y1 * \ln y_2)$	-0.01350	0.01244	-1.085	0.278

$I(\ln y1 * \ln z)$	0.31932	0.03472	9.198	<0.001
$I(\ln y1 * \ln w_1)$	-0.12176	0.10651	-1.143	0.253
$I(\ln y1 * \ln w_2)$	0.14310	0.09785	1.462	0.144
$I(\ln y2 * \ln z)$	-0.00745	0.00631	-1.181	0.238
$I(\ln y2 * \ln w_1)$	0.02098	0.01472	1.425	0.154
$I(\ln y2 * \ln w_2$	0.00304	0.01608	0.189	0.850
$I(\ln z * \ln w_1)$	-0.01486	0.05264	-0.282	0.778
$I(\ln z * \ln w_2)$	0.00139	0.04499	0.031	0.975
$I(\ln w1 * \ln w_2)$	-0.02578	0.10870	-0.237	0.813
t	0.00035	0.00045	0.786	0.432
t^2	-0.00006	0.00001	-4.997	<0.001
HHI	1.57237	0.39087	4.023	<0.001
Cycle	-0.00137	0.00092	-1.500	0.134
CPI	0.00258	0.00095	2.712	0.007

Panel B. Variance parameters

Parameter	Estimate
σ^2	0.00370
σ_u^2	0.00360
σ_v^2	0.00010
γ	0.96850

Panel C. Model statistics	
LogLik (ML)	712.93884
N	430
LR test $(H0:\ \sigma_u^2 = 0, df = 2)$	90.15903
Skewness test, H0: no inefficiency (z)	2.40196
Skewness test, H0: no inefficiency (p)	0.01631
Mean inefficiency E[exp(u)]	0.05982

Note: Panel B reports point estimates.

Source: Authors' estimates.

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Table 7: Cost Frontier Estimation Excluding the Dominant Bank

Panel A. Stochastic frontier (costs)

Parameter	Estimate	Standard error	z	p-value
Intercept	-1.28880	0.17041	-7.563	<0.001
$\ln y_1$	0.73667	0.03517	20.947	<0.001
$\ln y_2$	0.07924	0.00634	12.506	<0.001
ln z	-0.04063	0.02353	-1.727	0.084
$\ln w_1$	0.10768	0.04086	2.635	0.008
$\ln w_2$	0.68203	0.02933	23.257	<0.001
$I(0.5*\ln y_1^2)$	1.71320	0.17398	9.847	<0.001
$I(0.5*\ln y_2^2)$	0.05647	0.00556	10.153	<0.001
$I(0.5*\ln z^2)$	-0.32017	0.07960	-4.022	<0.001
$I(0.5*\ln w_1^2)$	-0.38960	0.16732	-2.328	0.020
$I(0.5*\ln w_2^2)$	0.20939	0.21575	0.971	0.332
$I(\ln y1 * \ln y_2)$	0.05204	0.01830	2.843	0.004
I(ln y1 * ln z)	0.13926	0.05984	2.327	0.020
$I(\ln y1 * \ln w_1)$	-0.32633	0.13567	-2.405	0.016
$I(\ln y1 * \ln w_2)$	0.73855	0.14617	5.053	<0.001
I(ln y2 * ln z)	0.00876	0.00922	0.950	0.342
$I(\ln y2 * \ln w_1)$	-0.01276	0.02015	-0.633	0.527
$I(\ln y2 * \ln w_2$	0.03338	0.02321	1.438	0.150
$I(\ln z * \ln w_1)$	-0.03172	0.06769	-0.469	0.639
$I(\ln z * \ln w_2)$	0.07638	0.07534	1.014	0.311
$I(\ln w1 * \ln w_2)$	0.02538	0.16095	0.158	0.875
t	-0.00028	0.00071	-0.398	0.691
t^2	-0.00003	0.00002	-1.462	0.144
HHI	2.02690	0.64213	3.157	0.002
Cycle	-0.00355	0.00145	-2.456	0.014
CPI	0.00066	0.00170	0.390	0.696

Panel B. Variance parameters

Parameter	Estimate
σ^2	0.00380
σ_u^2	0.00630
σ_v^2	0.00040
γ	0.93670

Panel C. Model statistics	
LogLik (ML)	571.00032
N	358
LR test $(H0\colon\ \sigma_u^2 = 0, df = 1)$	21.44075
Skewness test, H0: no inefficiency (z)	1.05425
Skewness test, H0: no inefficiency (p)	0.29177
Mean inefficiency ***E[exp(u)]***	0.06347

Note: Panel B reports point estimates.

Source: Authors' estimates.

Table 8: Regularity Tests for the Cost Function

Criterion	**Half-normal (baseline)**	**Exponential**	**Gamma**	**Without dominant bank**
Min. deposit (s1)	-0.2948	-0.0842	0.0595	-0.2628
Min. capital (s2)	0.4540	0.5371	0.5521	0.3672
Min. labor (s3)	-0.2164	-0.2564	-0.2609	-0.0770
Monotonicity (%)	70.0000	54.9000	51.6000	68.8000
s1 ≥ 0(%)	89.8000	99.3000	100.0000	74.0000
s2 ≥ 0(%)	100.0000	100.0000	100.0000	100.0000
s3 ≥ 0(%)	80.2000	55.6000	51.6000	94.9000
Local conc (%)	99.8000	100.0000	100.0000	32.3000
λmax (p95)	-0.0448	-0.0793	-0.0428	0.2705
λmax (max.)	0.0125	-0.0499	-0.0031	0.3962

Note: Monotonicity and concavity rates represent the percentage of observations for which the corresponding condition is satisfied. si denotes the implied share of input i in total cost. λmax corresponds to the largest eigenvalue of the Hessian matrix with respect to prices.

Source: Authors' estimates.

Tabla 9: Gamma Specification: Summary Robustness Results

Statistic	Gamma
σ^2	0.01250
σ_u^2	0.01230
σ_v^2	0.00020
γ	γ 0.98650
LogLik (ML)	729.64467
LR test $(H0:\ \sigma_u^2 = 0,\ df = 2)$	123.57068
Skewness test, H0: no inefficiency (z)	2.40196
Skewness test, H0: no inefficiency (p)	0.01631
Mean inefficiency E[exp(u)]	0.04947
Spearman's ρ vs. Half-Normal	0.829
p-value	0.058

Note: The Gamma specification is reported as a complementary robustness exercise. Since standard errors for several coefficient estimates were not fully identified, the model is used only to assess the stability of aggregate variance parameters, mean inefficiency, and relative rankings, rather than for coefficient-level inference. Source: Authors' own calculations.

Source: Authors' estimates.