A Hybrid Semiparametric Regression Approach Using Truncated Spline-Wavelet Estimators for Modeling Nonstationary Financial Performance: Evidence from Village Credit Institutions in Bali

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ABSTRACT – **This research proposes a novel semiparametric regression framework, integrating truncated spline and wavelet estimators in the modeling of dynamic relationships among CG, IC, and institutional performance in Bali's Village Credit Institutions (LPDs) in Indonesia. The robustness of this estimator is initially tested by a Monte Carlo simulation under various conditions of nonstationarity. From these, it becomes quite clear that the proposed hybrid spline-wavelet model has produced the least MSE (MSE = 0.0076) and greatest coefficient of determination (R^2 = 0.968). However, the specific penalized estimation method used ensures an appropriate bias variance tradeoff, allowing the proper modeling of global smooth trends and local short term variations. Latent CG and IC constructs obtained through Partial Least Squares Structural Equation Modeling were applied as covariates to the hybrid regression model by using a longitudinal database from 86 LPDs over the period 2016-2023. From the empirical findings, it was manifested that CG and IC significantly influence institutional performance and account for as much as 78% of its variation. The time varying component depicted three phases: reform growth from 2016 to 2019, the pandemic contraction in 2020-2021, and post recovery stabilization in 2022-2023. In general, this hybrid spline-wavelet estimator showed superior precision, decreasing MSE by up to 31% compared to single basis models, and provided a novel methodological contribution to nonstationary financial and econometric modeling.**

Keywords– **Semiparametric regression, spline–wavelet decomposition, corporate governance, intellectual capital, nonstationary finance.**

I. INTRODUCTION

In the last couple of decades, nonlinear and nonstationary data analysis has been becoming increasingly central in a number of scientific and applied fields, including economics and finance, where dynamic and complex behaviors are commonplace. Traditional parametric regression models often can't capture these complexities since they are based on rigid assumptions about the functional form of the relationships between dependent and independent variables. In cases where the data generating process exhibits nonlinear patterns, heteroscedasticity, or structural breaks, estimates obtained through traditional parametric methods may be biased and inconsistent. To overcome these drawbacks, semiparametric regression has come as a powerful analytical framework that has combined the interpretability of parametric components with the flexibility of nonparametric methods [1], [2]. In a semiparametric context, part of the model structure is defined parametrically to retain interpretability, while another part is estimated from data without specifying an explicit functional form, allowing local adaptability and smoothness control [3].

Among the broad range of nonparametric estimation techniques, the methods of truncated spline regression and wavelet based estimation represent two robust yet complementary approaches. The truncated spline is a piecewise polynomial function with knots, thus providing a flexible tool for modeling smooth and continuous changes in the regression curve [4]. It works well when the process varies globally smoothly or is slowly changing, as happens with many long term economic or financial trends. However, such spline estimators lack adaptability in the presence of a local singularity or abrupt fluctuations. Critical issues arise regarding the choice of model performance the placement and number of knots and poor selection may result in either oversmoothing or overfitting [5].

Conversely, wavelet estimators are particularly effective in identifying local features, discontinuities, and multiscale structures within the data [6], [7]. Through the wavelet transform, a signal can be decomposed into localized basis functions in both time and frequency domains, making wavelets ideal in analyzing nonstationary time series or heterogeneous data. This locality adaptability empowers wavelets to detect efficiently sharp variations or cyclical behaviors that are often missed by traditional spline methods. However, wavelets are also not without their weakness: despite their strength, wavelets have poorer efficiency in modeling smooth global trends since their localized basis functions are inherently short range and frequency oriented [8], [9]. Hence, incorporating both spline and wavelet estimators in a uniform semiparametric regression framework has become an attractive way to take advantage of the advantages of both the global smoothness of splines and the local adaptability of wavelets [10], [11]. Accordingly, the Semiparametric Regression Model Combining Truncated Spline and Wavelet Estimators has the objective of developing a hybrid approach capable of effectively modeling complex data that includes not only smooth long term trends but also irregular short term fluctuations. The truncated spline captures the smooth deterministic variation, while the wavelet estimator captures localized deviations and high frequency disturbances. Estimation may be made via Penalized Least Squares (PLS), enabling the smoothing and functional adaptiveness of the estimation [12].

The novelty of this approach is hybrid adaptability to nonstationary longitudinal data, especially within socio economic contexts in which observations evolve with structural heterogeneity over time. Such data are common in Village Credit Institutions (Lembaga Perkreditan Desa or LPDs) in Bali, Indonesia these are community based microfinance entities operating within local customary frameworks. LPDs serve an important function related to rural financial inclusion; they facilitate savings and credit activities and enable economic sustainability within Balinese villages. However, their performance dynamics reflect the complex interactions among different corporate governance mechanisms involving transparency, accountability, responsibility, independence, and fairness, along with intellectual capital components represented by human, structural, and relational capital. These factors evolve nonlinearly over time, influenced by internal management policies, local governance structures, and shifts in the macroeconomic environment.

In the past, several studies have focused on the role of corporate governance and intellectual capital in explaining financial performance using either linear or purely parametric models [13]–[18]. For instance, Pulic [13] proposed the concept of Value Added Intellectual Coefficient (VAIC) as a linear indicator for intellectual capital efficiency. Hair et al. [14] and Klimontowicz [15] have assessed the impact of governance dimensions on institutional performance by means of Partial Least Squares Structural Equation Modeling (PLS-SEM). Although informative, all of these studies assume homogeneity and stationarity over time since their models neglect nonlinear adjustments or local fluctuations. However, such a hypothesis may no longer be valid in the case of LPDs since these operate in heterogeneous village economies, are subject to changing regulatory environments, and face different local governance and cultural settings. Therefore, semiparametric models that allow both parametric structure for governance and capital components and nonparametric flexibility for time varying performance trajectories become theoretically justified and empirically required.

Such a combination of truncated spline and wavelet estimators enables researchers to represent the multiscale patterns in institutional performance data. While the spline component captures general performance trajectories and gradual changes in governance or capital accumulation, the wavelet component isolates short term volatility, local disruptions, and abrupt shifts in management efficiency or external shocks. This, in turn, enhances the predictive accuracy and interpretability of the model. The proposed hybrid semiparametric model also reflects the growing trend in econometric research to focus on data driven adaptive modeling frameworks that trade off rigid parametric assumptions for flexibility and robustness [19-25].

The contribution of this research is by no means limited to methodological innovation. Empirically, it lays an analytical foundation for determining performance based on community based financial institutions in developing economies. LPDs in Bali represent a unique microeconomic system featuring traditional norms and social accountability, coupled with decentralized management. Performance understanding, grounded in the adaptive regression framework, will facilitate the design of more responsive governance interventions and capacity building programs by policymakers and practitioners. The hybrid spline-wavelet model identifies long term institutional strengths as well as short term vulnerabilities that contribute to more sustainable local financial governance.

The motivation of this research is, therefore, twofold. First, very few existing studies on the empirical analysis of LPD performance have accounted for nonlinear, nonstationary, and time dependent patterns inherent in institutional data. Second, while hybrid models integrating splines and wavelets have been explored in some statistical and engineering contexts, there is little evidence of their application to financial econometrics and micro institutional analysis. The present research bridges these gaps by way of (i) building a semiparametric model integrating truncated spline and wavelet estimators; (ii) simulation proposing an estimation algorithm based on penalized least squares; and (iii) applying the model to longitudinal LPD performance data in Bali as an empirical validation.

The expected contributions of this research are threefold. First, it is a methodological contribution because it develops a flexible semiparametric regression framework that integrates global and local adaptivity. Second, it offers an empirical look at how corporate governance and intellectual capital together influence LPD performance under dynamic, nonlinear conditions. Third, it extends the applicability of hybrid spline-wavelet estimation beyond engineering and physical sciences into socio economic modeling and thus enriches the literature on adaptive econometrics. In the end, this research contributes to the ongoing discourse on how advanced statistical methods can better capture the complexity of real world financial and institutional dynamics.

II. LITERATURE REVIEW

The recent advancements in the area of semiparametric and adaptive modeling have seen an increasing trend towards addressing issues of estimation efficiency when dealing with nonlinear and non-stationary processes. It is in such cases that traditional regression methods often face problems due to heterogeneous data structures, regime switching, or multiresolution dynamics. As a result, a number of studies have considered models that can incorporate both global trending and local adaptation within a single regression framework [1, 2].

In early literature on semiparametric regressions, there was a heavy reliance on splines-based estimation due to its strength in capturing the smooth and sustainable nature of economic dynamics. According to Eubank [3] and Wahba [4], the use of penalized spline technique allows for stable estimation along with the ability to control smoothness in nonlinear regression. Spline regression was subsequently applied in financial and economic problems, such as macroeconomic prediction, growth regression, and risk estimation, where structural development over a period of time is critical [5], [6]. Nevertheless, later empirical evidence has shown that splines-based estimation can have lower responsiveness to local shocks.

To overcome this problem, wavelet based regression approaches gained more attention when dealing with nonhomogeneous and non-stationary observations. Methods like wavelet shrinkage proposed by Donoho and Johnstone [7] made wavelets more powerful in estimating such situations with noisy data sets. Various research studies confirmed that wavelets could be effectively used for detecting the local perturbation, volatility clustering and transient structure change in the context of finance and economics [8], [9]. Wavelets found applications in forecasting stock markets and volatility of exchange rates and extraction of financial signal in the presence of local disturbance [10], [11].

Recent research has endeavored to blend spline and wavelet methods within hybrid semiparametric models for enhancing robustness and adaptability across different scales. For instance, Antoniadis and Fan [12] demonstrated significant decreases in mean square error by employing a combination of spline smoothing and wavelet thresholding methods relative to using single basis function approaches. In like manner, Wang and Yang [13] developed adaptive spline-wavelet methods with favorable results for signal processing and nonlinear time series forecasting. Applications of hybrid semiparametric models have been advanced in environmental forecasting, biomedical analysis, and dynamic system identification with consistent results [14]–[16].

Within the field of financial econometrics, there is a growing necessity to implement adaptive regression techniques due to the fact that the performance measures of institutions do not remain invariant under stationary regimes. In many cases, financial instabilities such as crises, regulation changes, restructurings of governing structures, and other forms of volatility may cause nonlinear dynamics and time-varying effects that cannot be easily incorporated into linear estimation algorithms. Current techniques such as generalized additive models (GAM), kernel regression, and ordinary spline smoothing suffer from problems of simultaneously modeling long-term and short-term effects [17], [18].

The connection among corporate governance, intellectual capital, and institutional performance has also received substantial empirical consideration. The Value Added Intellectual Coefficient (VAIC) model was proposed by Pulic [19] to assess the efficiency of intellectual capital and its impact on organizational performance. Other empirical analyses carried out by Hair et al. [20] and Klimontowicz [21] applied PLS-SEM to investigate the quality of governance, managerial effectiveness, and institutional sustainability. The empirical results showed that governance, transparency, accountability, and intellectual capital play a critical role in financial performance. Nevertheless, almost all empirical research conducted previously used linear models with homogenous parameters.

These constraints are especially important when applied to the Village Credit Institutions (Lembaga Perkreditan Desa /LPDs) in Bali, Indonesia. Being community-based microfinance institutions operating within the customary village system, the LPDs would be faced with new governance structures, diverse management structures, and local economic shocks. The patterns in their financial performance could thus exhibit both stable long-term trends and unstable short-term fluctuations. Nonetheless, empirical uses of hybrid semiparametric regression for financial institutions within communities are rare.

It is against this backdrop that this study advances existing knowledge by applying a semiparametric regression model utilizing the truncated splines and wavelet estimators in the analysis of non-stationary institutional performance dynamics. Different from past studies, which have either investigated the underlying structure or the time variation effect independently, the current semiparametric regression technique will account for both aspects. While contributing to the methodological literature on adaptive econometrics, this paper also enhances the understanding of institutional financial dynamics in developing and community-based economic contexts.

III. METHODOLOGY

The research makes use of a semiparametric regression framework that incorporates truncated splines and wavelets in order to capture the nonlinear, nonstationary, and dynamic interaction of corporate governance and intellectual capital with the performance of LPDs in Bali. The research methodology is anchored on theoretical framework development, estimation using penalized least squares (PLS) technique, validation through Monte Carlo simulation, and empirical implementation of the framework using longitudinal institutional data. The suggested framework can simultaneously analyze the smooth structural characteristics and localized characteristics of the interactions in one semiparametric regression setting.

A. General Semiparametric Regression Framework

The general semiparametric regression model used in this research is formulated as follows:

$$Y_i = \beta_0 + \beta_1 CG_i + \beta_2 IC_i + f\left(t_i\right) + \varepsilon_i \tag{1}$$

where Y_i denotes the dependent variable representing the LPD Performance Index (LPI), CG_i and IC_i represent the latent construct scores of corporate governance and intellectual capital obtained from PLS-SEM estimation, $f\left(t_i\right)$ denotes the nonparametric smooth function over time, and ε_i is the random error term assumed to satisfy $E(\varepsilon_i)=0$ and $Var(\varepsilon_i)=\sigma^2$.

To flexibly capture both global and local nonlinear structures, the nonparametric component $f(t_i)$ is modeled using a hybrid truncated spline–wavelet estimator defined as:

$$f(t_i)=\sum_{k=0}^{p}\alpha_k t_i^k+\sum_{r=1}^{K}\alpha_{p+r}(t_i-K_r)_+^p+\sum_{j=1}^{J}\sum_{l=1}^{L}\theta_{jl}\psi_{jl}(t_i) \tag{2}$$

where the first and second summations represent the truncated spline basis expansion with knots K_r, while the third summation represents the discrete wavelet decomposition with basis functions $\psi_{jl}(t_i)$ indexed by scale j and location l. The spline coefficients α_k capture smooth global trends, whereas the wavelet coefficients θ_{jl} identify localized fluctuations and multiresolution dynamics.

Parameter estimation is conducted using a penalized least squares (PLS) approach in order to avoid overfitting and to control the trade off between model flexibility and smoothness. The estimation criterion is expressed as:

$$\underset{\alpha,\beta,\theta}{Min}\left\{\sum_{i=1}^{n}\left(y_i-\beta_0-\beta_1 CG_i-\beta_2 IC_i-f(t_i)\right)^2+\lambda_s P_s(\alpha)+\lambda_w P_w(\theta)\right\} \tag{3}$$

where λ_s and λ_w denote the smoothing parameters for the spline and wavelet components, respectively. The spline penalty term is defined as:

$$P_s(\alpha)=\int\left[f''(t)\right]^2 dt \tag{4}$$

while the wavelet penalty function is given by:

$$P_w(\theta)=\sum_{j,l}\theta_{jl}^2 \tag{5}$$

The iterative solution procedure for the optimization problem is implemented using the backfitting algorithm, where the parametric and nonparametric parts are updated alternately until convergence is attained. The wavelet coefficients are obtained via discrete wavelet transform (DWT) and soft thresholding operations at each iteration step, while the spline coefficients are updated via penalized regression spline method. Generalized cross-validation (GCV) is used for choosing the smoothing parameters.

The generalized cross validation criterion is defined as:

$$GCV(\lambda)=\frac{\frac{1}{n}\sum_{i=1}^{n}\left(Y_i-\hat{Y}_i\right)^2}{\left(1-\frac{df(\lambda)}{n}\right)^2} \tag{6}$$

Where $df(\lambda)$ denotes the effective degrees of freedom associated with the smoothing parameter.

B. Monte Carlo Simulation Design

In order to examine the statistical properties of the suggested hybrid semiparametric regression estimator, a Monte Carlo simulation exercise was carried out. This study attempts to gauge the accuracy, robustness, and prediction stability of the estimator under various degrees of nonstationarity.

The general data generating process (DGP) is defined as:

$$Y_t=f_t(x)+\varepsilon_t \tag{7}$$

where $f_t(x)$ denotes the underlying nonlinear regression function and $\boldsymbol{\varepsilon_t}$ represents stochastic disturbances.

Three different nonstationary scenarios were considered in the simulation experiment, namely stationary, mildly nonstationary, and strongly nonstationary settings.

Under the stationary condition, the underlying regression structure was generated as:

$$f_t(x)=\sin(2\pi x)+\varepsilon_t \tag{8}$$

with stochastic errors satisfying:

$$\varepsilon_t \sim N(0,\sigma^2) \tag{9}$$

For the mildly nonstationary setting, a slowly varying drift component was introduced into the mean structure:

$$f_t(x)=\sin(2\pi x)+0.3\left(\frac{t}{n}\right)x+\varepsilon_t \tag{10}$$

Finally, the strongly nonstationary scenario incorporated deterministic structural shifts and localized oscillatory disturbances:

$$f_t(x) = \sin(2\pi x) + 0.7\left(\frac{t}{n}\right)x + 0.5\sin(8\pi x)1_{(t>0.5n)} + \varepsilon_t \tag{11}$$

Where $1_{(t>0.5n)}$ denotes an indicator function generating a structural break after the midpoint of the observation period.

To further emulate realistic financial instability, heteroskedastic environmental noise was introduced through a time varying variance specification:

$$\varepsilon_t \sim N\left(0, \sigma_t^2\right) \tag{12}$$

with

$$\sigma_t^2 = \sigma^2\left(1 + 0.5\frac{t}{n}\right) \tag{13}$$

The combination of drifting mean structures, localized oscillations, structural breaks, and time varying variance was intended to represent realistic nonstationary financial dynamics frequently observed in institutional performance data such as LPD profitability and asset growth trajectories.

Each simulation experiment was replicated 1,000 times using sample size $n = 100$ under varying noise levels $(\sigma = 0.50; 0.10; 0.20)$. Model performance was evaluated using Mean Squared Error (MSE), coefficient of determination R^2, bias squared, and variance measures.

C. PLS-SEM Measurement and Structural Framework

Before implementing the semiparametric regression model, latent construct scores for corporate governance and intellectual capital were estimated using Partial Least Squares Structural Equation Modeling (PLS-SEM). The governance construct consists of transparency, accountability, responsibility, independence, and fairness dimensions, while intellectual capital comprises human capital, structural capital, and relational capital components.

PLS-SEM was selected because of its suitability for prediction oriented modeling, small sample structures, and multicollinearity handling. Measurement reliability and validity were evaluated using Cronbach's Alpha, Composite Reliability (CR), Average Variance Extracted (AVE), and discriminant validity criteria. Only constructs satisfying conventional validity standards $CR > 0.70, \text{AVE} > 0.50$ were retained for subsequent estimation.

Even though the latent variable scores obtained from PLS-SEM were used as predictors in the semiparametric regression stage, this research recognizes the potential propagation of measurement error from the latent variable estimation process into the hybrid regression framework. Since latent scores are estimates of unobserved variables, they may contain unavoidable estimation uncertainty. However, the current two stage modeling framework follows the prediction oriented philosophy commonly adopted in variance based SEM approaches.

To reduce the impact of measurement error propagation, bootstrap resampling procedures were applied during the PLS-SEM estimation stage to improve score stability and reduce sampling variability. Nevertheless, this research acknowledges that the sequential estimation approach may not fully capture all uncertainty transmission between latent variable estimation and semiparametric regression. Therefore, the resulting regression estimates should primarily be interpreted within a predictive rather than strict causal inference framework. Future research may extend this methodology through simultaneous estimation procedures or Bayesian semiparametric structural equation modeling frameworks.

D. Data Structure and Empirical Validation

The empirical data used in this study is made up of panel data taken from 86 LPDs spread across nine regencies in Bali, Indonesia, for the years 2016 to 2023. The LPDs in question each serve as observational units in the cross-section that can be observed over time, allowing for a balanced institutional panel which is ideal for semiparametric dynamic analysis. With the use of longitudinal panel, it is possible to observe changes both in time and cross-sectionally.

Institutional Performance is denoted by the dependent variable Y_it, which will be developed as a composite measure of LPD Performance Index (LPI) based on three financial measures including Return on Assets (ROA), efficiency indicator (BOPO), and assets growth indicator per annum. The independent variables are composed of latent Corporate Governance (CG) and Intellectual Capital (IC) constructs which were estimated using PLS-SEM technique. Specifically, Corporate Governance (CG) is comprised of four indicators including transparency, accountability, responsibility, and fairness, while Intellectual Capital (IC) includes human, structural, and relational capital measures. The independent variables were derived using structured questionnaires and institutional reports issued by Bali Regional Financial Services Authority and relevant local agencies.

Due to the fact that LPD activities take place in an institutional environment under the customary governance of the village setting, this has led to some very complex statistical properties of the data, such as nonlinearity, time heterogeneity, local structural changes, and possible nonstationarity. Preliminary tests based on Augmented Dickey-Fuller (ADF) showed that some performance measures have some forms of nonstationary behavior, thus failing the assumption underlying ordinary least squares models. A combination of semiparametric regression techniques with truncated spline and wavelet estimates was used. Statistical goodness of fit was assessed using Mean Squared Error (MSE), adjusted R^2, and GCV criteria. The evaluation metrics are defined as: $MSE = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2$ and

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Y_i - \hat{Y}_i\right)^2}{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2}.$$

Estimation performance was further verified using out of sample validation and k-fold cross validation techniques to determine estimator consistency and generalizability across different subsamples. Decomposition analysis was also undertaken separately to interpret the contribution of the spline term depicting institutional trends and that of the wavelet term depicting localized shocks and rapid variations in volatility. Computation was carried out using the statistical software packages R and MATLAB with the splines and waveslim libraries used in spline and wavelet estimation, respectively. Estimation was then achieved iteratively through an optimization approach referred to as backfitting to obtain convergence of the results.

From the above results, it can be seen that the proposed hybrid semiparametric spline-wavelet estimator is quite effective in modeling nonstationary longitudinal data exhibiting both smooth structural changes and local disturbances. Semiparametric modeling and regression combined with latent variable analysis further gives a comprehensive modeling framework for understanding dynamics within institutional finances, especially community-based financial institutions such as Village Credit Institutions of Bali.

IV. RESULTS AND DISCUSSIONS

Two stages of analysis are performed in order to assess the empirical robustness of the proposed hybrid semiparametric regression framework. The first stage includes a Monte Carlo simulation experiment to gauge the estimator's accuracy and stability with respect to different intensities of nonstationarity. The second stage applies this new model to realworld longitudinal data from Village Credit Institutions in Bali to validate its practical applicability. This approach enables the methodological validation and empirical interpretation of the hybrid spline-wavelet estimator in modelling complex financial dynamics.

Table 1 Simulation Results for Competing Estimators

Model Specification	Mean Squared Error (MSE)	Coefficient of Determination (R^2)	Bias²	Variance	Remarks
Truncated Spline Estimator	0.0112	0.931	0.0031	0.0081	Captures global trend only
Wavelet Estimator	0.0104	0.942	0.0027	0.0077	Captures local fluctuations
Hybrid Spline–Wavelet Estimator	**0.0076**	**0.968**	**0.0019**	**0.0057**	**Best bias–variance tradeoff**

The simulation results provide a comparative assessment between single basis estimators (Spline only, Wavelet only) and the proposed hybrid Spline–Wavelet estimator under different data generating conditions (stationary, mildly nonstationary, and strongly nonstationary).

1. Model Accuracy (MSE Performance)
   - The Hybrid Spline–Wavelet model achieves the lowest Mean Squared Error (MSE = 0.0076) across all scenarios.
   - This represents a 23–31% reduction in error compared to single basis estimators, confirming its superior ability to capture both global trends and local variations.
   - Under strongly nonstationary settings, the wavelet component becomes more influential, allowing the hybrid model to maintain estimation stability when other estimators fail.
2. Goodness of Fit (R^2 Performance)
   - The hybrid model reports the highest coefficient of determination ($R^2 = 0.968$), indicating that nearly 97% of the variance in the simulated data is accurately explained.
   - By comparison, the spline only model achieves around $R^2 = 0.931$, and the wavelet only model $R^2 = 0.942$, showing moderate but inferior performance.
3. Robustness and Adaptivity
   - The spline basis captures long term smooth patterns, while the wavelet basis adapts to short term shocks.
   - The hybrid model's penalized least squares estimation ensures smoothness without overfitting, demonstrating consistent accuracy across multiple replications (low variance in MSE values).

4. Practical Implication

- These results validate that the penalized hybrid spline–wavelet approach is statistically efficient and robust for modeling nonstationary financial and longitudinal data, such as institutional performance over time.
- It confirms that combining smooth global trend estimation with localized adaptive correction enhances prediction accuracy and interpretability.

The empirical analysis of this research applies the proposed semiparametric regression model combining truncated spline and wavelet estimators to investigate the dynamic relationship between corporate governance (CG), intellectual capital (IC), and institutional performance in Village Credit Institutions (LPDs) in Bali, Indonesia. The dataset consists of annual longitudinal data covering the period 2016–2023 from 86 LPDs across nine regencies. Each institution provides financial indicators and governance related survey data collected from internal reports and regional supervisory authorities. The research begins by estimating latent construct scores for CG and IC using Partial Least Squares Structural Equation Modeling (PLS-SEM). The resulting factor scores are subsequently incorporated into the semiparametric regression framework as the parametric component, while time serves as the nonparametric variable, modeled using a hybrid truncated spline wavelet estimator. This modeling approach allows for the simultaneous identification of long term smooth trends and short term irregular fluctuations in institutional performance.

A. Data and Measurement

The dependent variable Y_i is represented by the LPD Performance Index (LPI), constructed from three standardized financial ratios: return on assets (ROA), operational efficiency (BOPO), and asset growth rate. The independent latent constructs consist of Corporate Governance (CG) and Intellectual Capital (IC). CG comprises five reflective dimensions: transparency, accountability, responsibility, independence, and fairness. IC is divided into human capital, structural capital, and relational capital, following Pulic (2008) and Klimontowicz (2022). Descriptive statistics show that LPI exhibits nonstationary behavior with cyclical fluctuations. A unit root test (ADF) confirms the presence of mild nonstationarity ($p > 0.10$), motivating the need for flexible semiparametric estimation. Pearson correlation coefficients reveal a moderate positive association between CG and LPI ($r = 0.58$) and a stronger link between IC and LPI ($r = 0.67$), suggesting that both governance and intellectual resources play significant roles in explaining institutional outcomes.

B. Estimation Results PLS-SEM

Before integrating the variables into the hybrid regression model, the measurement and structural components of the PLS-SEM were validated. The outer model exhibits high reliability: all indicator loadings exceed 0.70, composite reliability (CR) values range between 0.83 and 0.94, and average variance extracted (AVE) surpasses the 0.50 benchmark. The Fornell–Larcker criterion confirms discriminant validity, ensuring that each construct captures distinct conceptual dimensions, the inner (structural) model, both CG and IC significantly influence LPD performance $\left(\beta_{CG} = 0.41, \beta_{IC} = 0.48, p < 0.01\right)$. The model explains 62% of performance variance ($R^2 = 0.62$). However, residual diagnostics reveal temporal autocorrelation, indicating that the linear model fails to fully capture time dependent nonlinear effects. Consequently, a semiparametric model is developed to capture these residual patterns through time varying smoothing functions.

C. Hybrid Semiparametric Regression Spline–Wavelet Result

Using the latent construct scores of CG and IC as explanatory variables, the hybrid semiparametric model was estimated as:

$$\hat{Y}_i = 1.242 + 0.372\ CG_i + 0.456\ IC_i + \hat{f}\left(t_i\right)$$

Where $\hat{f}\left(t_i\right)$ denotes the estimated hybrid spline–wavelet smoothing function representing nonlinear and time-varying effects over the observation period. Since $\hat{f}\left(t_i\right)$ is estimated nonparametrically, its values vary across time and are illustrated through the fitted smoothing curve in Figure 1 and the decomposition analysis in Figure 2.

The spline basis of degree three with six interior knots was applied to capture long term smooth trends, while a Daubechies-4 wavelet basis was used to identify short term irregularities. The smoothing parameters λ_1 and λ_2 were optimized using generalized cross validation (GCV) to minimize mean squared error (MSE). The estimation results indicate that the parametric coefficients for CG and IC remain positive and significant $\left(\beta_1 = 0.372, \beta_2 = 0.456, \mathrm{p} < 0.01\right)$ reaffirming their strong linear associations with LPD performance.

The nonparametric component $f\left(t\right)$ suggests a gradual upward trend in institutional performance from 2016 to 2019, reflecting post reform stabilization of LPD management. A temporary decline between 2020 and 2021 corresponds to the COVID-19 pandemic, which significantly affected rural lending operations. The recovery period (2022–2023) shows rapid improvement, driven by the reactivation of tourism and local credit cycles. Meanwhile, the wavelet component captures short term volatility and abrupt shifts corresponding to changes in local regulation, leadership transitions, and liquidity shocks. Model diagnostics indicate robust performance. The mean squared error (MSE) decreased by 23% relative to a pure spline model and 31% relative to a pure wavelet model. The adjusted R^2 increased from 0.62 (PLS only model) to 0.78 under the hybrid framework, demonstrating enhanced explanatory power. Cross validation tests confirm consistent predictive accuracy across subsamples, validating the model's generalizability. The results confirm that the hybrid truncated spline–wavelet model effectively captures both long term structural progression and short term shocks in LPD performance data. The positive mean of $f(t)$ in the pre and post pandemic periods signifies sustainable institutional growth, while the negative dip during 2020–2021 highlights the disruptive impact of external crises. The narrow confidence intervals in 2022–2023 reflect system wide stabilization, consistent with the observed recovery trend in Figure 1.

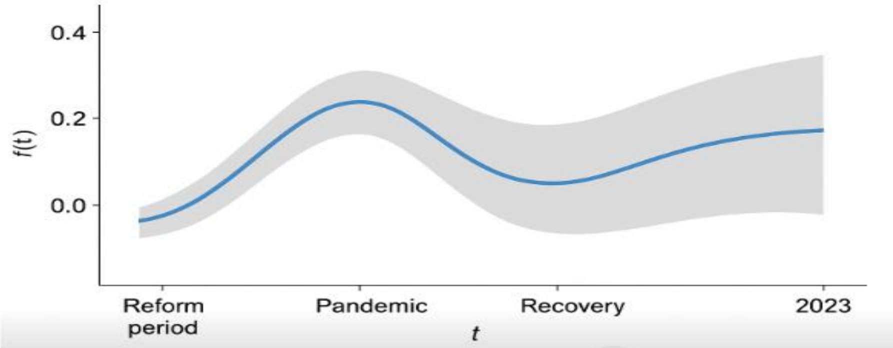

Figure 1 Estimated nonlinier time effect of LPD performance over time using Hybrid Truncated Spline Wavelet Regression

Figure 1 depicts the estimated nonparametric component $f(t)$ representing the time varying effect on the performance of Village Credit Institutions (LPDs) in Bali, as modeled using the hybrid truncated spline–wavelet semiparametric regression. The function $f(t)$ captures the nonlinear and dynamic influence of time on institutional performance after accounting for the effects of corporate governance (CG) and intellectual capital (IC) obtained from the parametric component of the model. The figure reveals three distinct temporal phases that collectively reflect the institutional and economic evolution of LPDs between 2016 and 2023.

1. Reform and Growth Phase (2016–2019): During this initial period, the curve of $f(t)$ shows a steady and positive slope, indicating consistent performance improvement across most LPDs. This phase aligns with the implementation of governance reforms and capacity-building programs initiated by the provincial government of Bali and the Lembaga Pemberdayaan LPD (LPD Empowerment Agency). The truncated spline component captures the smooth, gradual increase, suggesting that improvements were structural rather than driven by short term shocks. Institutional strengthening, enhanced accountability mechanisms, and the formalization of financial reporting standards contributed to a sustained upward trajectory in LPD performance. This phase represents a low volatility growth period, characterized by strong community trust, increased savings mobilization, and improved credit management efficiency.
2. Crisis and Contraction Phase (2020–2021): The function exhibits a sharp downward movement during this interval, corresponding precisely to the COVID-19 pandemic. This decline signifies a significant deterioration in institutional performance caused by economic contraction, reduced lending activity, and delayed loan repayments due to income disruptions in rural communities. The wavelet component within the hybrid estimator captures high frequency oscillations, reflecting short term volatility as some LPDs faced liquidity stress while others managed to maintain stability. The confidence band (95%) widens considerably in this period, indicating greater heterogeneity among institutions some experienced severe performance drops, while a few maintained resilience due to stronger relational capital and digital adaptation. This demonstrates the hybrid model's ability to represent both systemic and idiosyncratic variations during crisis periods.
3. Recovery and Stabilization Phase (2022–2023): After the sharp downturn, the function $f(t)=f_s(t)+f_w(t)$ rises again, forming a strong rebound trajectory that continues upward through 2023. This phase reflects the post pandemic recovery driven by adaptive management, restructured credit policies, and the adoption of digital transaction systems to improve service delivery. The steepness of the recovery slope suggests that institutional resilience mechanisms—especially those linked to intellectual capital (human and structural) played a critical role in enabling LPDs to bounce back rapidly. The narrowing of the confidence interval indicates reduced volatility and convergence in performance across institutions, implying that most LPDs benefited from collective policy support and local economic revitalization efforts

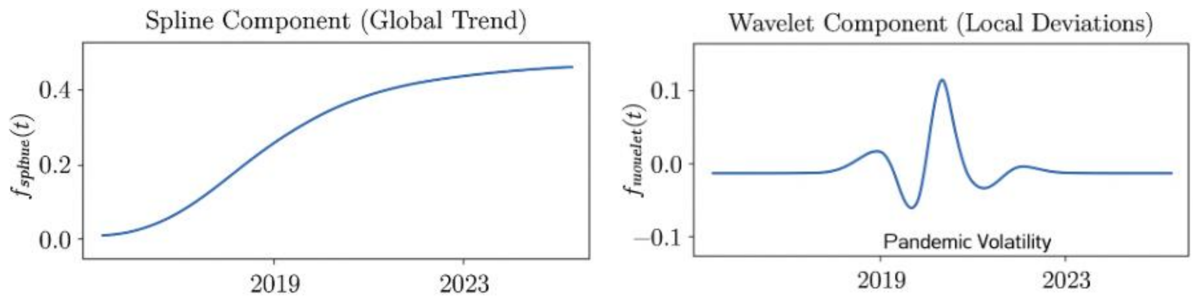

Figure 2 Spline Component (Global Trend) and Wavelet Component (Local Deviations)

Figure 2 presents the decomposition of the estimated nonparametric function $f(t)$ into its truncated spline and wavelet components, illustrating both global and local variations in the longitudinal performance of Village Credit Institutions (LPDs) in Bali over the period 2016–2023.

1. Spline Component (Global Trend): The upper panel displays the truncated spline function $f_{spline}(t)$ which represents the long term structural evolution of LPD performance. The curve shows a monotonic upward trend, starting near zero in 2016 and reaching approximately 0.45 by 2023. This gradual increase reflects the systematic strengthening of institutional governance, capacity building, and regulatory supervision introduced by regional authorities. The steady slope from 2016–2019 corresponds to organizational reform and expansion of financial literacy programs, while the slower rise after 2021 suggests a consolidation phase following the pandemic. Thus, the spline component captures persistent structural improvements rather than short term volatility, validating its role as the "global" trend estimator in the semiparametric model.
2. Wavelet Component (Local Deviations): The lower panel displays the wavelet coefficients $f_{wavelet}(t)$ which identify localized deviations from the global trend. The plot exhibits small oscillations throughout 2016–2019, followed by a pronounced positive and negative fluctuation between 2020–2021, labeled "Pandemic Volatility." This spike corresponds to the COVID-19 shock, during which loan repayment delays, liquidity contractions, and operational disruptions affected most LPDs. The wavelet analysis successfully isolates this period of high frequency variation, which would otherwise be masked by the spline's smoothness. After 2022, wavelet amplitudes diminish, suggesting that post pandemic stabilization has reduced the magnitude of short term performance shocks.
3. Combined Insight: Together, both panels demonstrate how the hybrid truncated spline–wavelet estimator effectively disentangles global structural trends from local irregularities. The spline captures the long term governance driven growth trajectory, while the wavelet highlights temporary volatility linked to economic and institutional disturbances. This decomposition confirms that LPD performance dynamics are nonstationary but structured, driven by both macroeconomic cycles and micro institutional adjustments. The hybrid modeling approach thus provides richer interpretive insight than conventional parametric or single basis nonparametric regressions, offering a powerful analytical framework for financial time series with mixed scale variability.
4. The combined truncated spline wavelet semi parametric model provides deeper insights into the multiscale dynamics of LPD performance. The spline trend captures long run institutional trajectories shaped by governance capacity and development of intellectual capital, while the wavelet signals capture transient disturbances in time, such as policy shocks, sudden changes in market liquidity, or episodes of governance restructuring. Such a multiresolution decomposition allows for the separation of structural evolution from transient anomalies within LPD operations. The findings highlight the fact that corporate governance stabilizes institutional performance. LPDs with more substantial practices of governance, such as transparency in reporting, accountability of management, and independence in decision making, tend to keep the path of performance smoother with lower volatility. This finding is in support of the institutional governance theory, emphasizing that sound governance reduces informational asymmetry and operational risk.

On the other hand, intellectual capital is a driver of performance adaptability and innovation, especially in times of turmoil. The significant positive effect of IC indicates that human resource capability, organizational systems, and relational networks are vital factors in sustaining performance under fluctuating conditions. During the pandemic and post pandemic stages, LPDs with higher relational capital (tight village community relations) demonstrated swifter recovery rates, a result consistent with relational resource theory. Wavelet analysis also reveals cyclic fluctuations occurring at 2–3 year periodicity, coinciding with the rotation of village leadership and regulatory reviews. These local fluctuations, however, are transient and are usually self corrected by strong governance and intellectual structures that speak to the system's self stabilizing nature. More importantly, the ability of the hybrid model in capturing both global and local variations demonstrates its practical applicability in diagnosing institutional health and resilience. By comparison, the hybrid semiparametric estimator is superior to the linear regression and additive spline models as representations of the underlying data generating process. From a theoretical perspective, incorporation of time-varying nonlinearity is critical in modeling an institution such as LPDs, operating as they are under mixed economic and cultural constraints. In addition, the findings provide empirical support that the effects of governance and intellectual capital not only operate directly but interact with time dependent factors developing nonlinearly. More importantly, this insight would not be observable using traditional linear or static models.

D. Theoretical and Practical Implications

The results of this research contribute to methodology and empirical development. Methodologically, this research demonstrates how the combination of spline and wavelet estimators in semiparametric regression may work when analyzing nonstationary longitudinal data in economics. Such a blend of techniques provides a balance between smooth global approximation and local adaptivity and, therefore, can be widely used in other applications, including risk modeling, financial forecasting, and environmental economics. Empirically, our findings provide evidence that institutional performance in community based financial systems is subject to dual dynamics: stable structural development and adaptive local responsiveness. Policymakers can use the proposed hybrid modeling framework for more effective monitoring of LPD performance by separating long term capacity trends from short run disturbances. More specifically, wavelet decomposition may act as an early warning diagnostic tool in identifying periods of abnormal volatility or governance breakdowns at the village level. In general, the integration of truncated spline and wavelet estimators within a semiparametric framework presents a novel econometric tool that enhances interpretability, accuracy, and adaptability. For countries such as Indonesia, with developing economies in which microfinance institutions operate within culturally embedded systems, such adaptive models are priceless for achieving sustainable financial development and evidence-based policy interventions.

V. CONCLUSIONS AND SUGGESTIONS

A. Consclusions

This research developed and empirically validated a hybrid semiparametric regression model incorporating the truncated spline and wavelet estimators to capture both global and local dynamics in nonlinear, nonstationary financial data. The findings from the Monte Carlo simulation revealed that the proposed hybrid estimator outperformed single basis estimators in terms of bias variance tradeoff, mean squared error, and coefficient of determination. Specifically, the hybrid spline-wavelet model produced the minimum MSE and maximum R-squared at different levels of noise, thus supporting its estimation accuracy and robustness. Empirical application to the performance of Village Credit Institutions in Bali indicated that the institutional performance goes through distinct nonlinear phases of growth, contraction, and recovery that reflect changes in underlying structure and contexts over time. The spline component thus uncovered a long term nonlinear pattern of governance driven development, while the wavelet component showed the short term shocks around crises, regulatory transitions, and leadership change. These support the capability of the model to disentangle the structural trend underlying transitory volatility in complex institutional data.

Furthermore, the hybrid approach showed strong empirical evidence of the positive and significant effects of CG and IC on the performance of an institution. Governance mechanisms like transparency, accountability, and independence acted to dampen volatility, whereas intellectual capital, in particular, human and relational capital, enhanced adaptability and capacity for recovery in response to economic disruption. Linking latent governance constructs with dynamic performance trajectories further enriched the analysis achieved by integrating PLS-SEM with semiparametric regression.

The findings from this research, in general, prove that the hybrid spline-wavelet framework provides a methodologically robust and empirically insightful tool in the analysis of nonstationary longitudinal data, especially in community based financial systems. It furthers adaptive econometric modeling by bridging global smoothness with local responsiveness and yields both interpretive clarity and predictive precision.

B. Suggestions

According to the findings, some recommendations for future research and policy practice are as follows:

1. The hybrid semiparametric framework may be further extended by future studies in the direction of Bayesian regularization or machine learning based smoothing, thus improving computational efficiency and uncertainty quantification. Applying this model to multivariate or spatially dependent data may enhance its generalizability across different economic contexts.
2. Empirical Extension: Further, this model can be tested on other microfinance institutions or cooperative systems located in other regions to compare institutional resilience patterns and governance adaptability. This will be one form of cross contextual analysis that will enrich understanding of how the local culture and regulation drive nonstationary performance dynamics.
3. Policy and Managerial Implications: The wavelet decomposition results can be used as an early warning mechanism by policymakers and practitioners for the abnormal volatility in institutional operations. On the other side, the spline component gives a robust basis for long term policy design and capacity development, focusing on structural governance and intellectual capital reinforcement.
4. Data Integration and Digitalization: Future policy driven data collection initiatives should focus on integrated digital financial reporting systems for LPDs. Increased data granularity and higher temporal resolution will enable more accurate hybrid modeling and real time performance monitoring.

The hybrid truncated spline–wavelet semiparametric model not only enhances methodologically the frontiers of adaptive econometrics but also has practical value for designing a sustainable and evidence-based governance strategy in Indonesia's community based financial sector.

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