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Research Article

ADAPTIVE MULTIRESOLUTION SEMIPARAMETRIC MODEL INTEGRATING TRUNCATED SPLINE AND WAVELET TO BALINESE VILLAGE CREDIT INSTITUTIONS (LPD)

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Abstract
In this research, an adaptive multiresolution semiparametric regression approach is proposed to examine the financial performance of Lembaga Perkreditan Desa (LPD) in Bali, Indonesia. In the research, the problem that arises from the inadequacy of traditional regression techniques in accounting for the nonlinear pattern in the data and the financial instability is overcome by introducing the truncated spline and wavelet components into the semiparametric regression analysis. This research utilizes a quantitative method based on secondary financial information collected for 50 LPDs between 2015 and 2024, providing around 500 observations. In order to obtain a more consistent dataset, the purposive sampling method will be used. Return on Assets (ROA) is chosen as the dependent variable, and explanatory variables include interest rates, the number of customers, capital adequacy ratio (CAR), total assets, and non performing loans (NPL). The model will be estimated using the penalized least squares with iterative backfitting estimation technique and will be assessed using the RMSE, MAE, and R^2 criteria based on Kfold cross validation. As it can be seen from the results, the hybrid model significantly improves the predictive power of traditional linear and spline methods, providing smaller error rates and better fit quality. Spline functions help to determine long term trends, whereas wavelets capture short term effects. This shows that multiresolution modeling increases predictability and interpretability. The model has practical utility for financial management and regulation through adaptive risk management and decision-making processes in microfinance firms.

Keywords: Adaptive Multiresolution, Balinese Village Credit Institutions, Penalized Estimation, Truncated Spline, Wavelet

INTRODUCTION

The Village Credit Institution (LPD) is a peculiar form of microfinance institution that functions under the existing system of governance in villages of Bali, Indonesia (Dewi et al,2024; Sugiartha et al., 2025; Anggreni et al., 2021). Contrary to regular financial institutions, LPDs are integrated into a socio cultural milieu where economic transactions are strongly linked to customary laws and local governance

(Sasmiharti, 2024; Wasiaturrahma, 2020; Loissa et al., 2023 Agustina et al., 2024; Sinarwati et al., 2022; Susanti et al., 2021). As a result of the distinct institutional framework, LPDs function as both financial intermediaries and catalysts for economic development at the local level. By providing savings and credit services, LPDs become instrumental for enabling the flow of capital in the economy and promoting small enterprises. In empirical studies, some of the financial factors of LPD performance include the interest rate, capital adequacy ratio, growth in the number of customers, and non performing loans (Sancaya et al., 2025; Anshar, 2023; Nugraha et al., 2022; Wiriastini et al., 2021; Barkah et al., 2025; Rafdi, 2026). At the same time, some forms of financial risks, such as liquidity and capital adequacy risks, can strongly affect the sustainability of institutions (Utami et.al., 2024; Widhiastuti et al., 2024; Putra et al., 2024).

Though the significance of these relationships is obvious, empirical studies still apply linear regression as the major statistical method. Indeed, linear regression can be easily estimated and interpreted. However, this model presupposes certain assumptions that are rather strict and might not reflect the real situation. In particular, financial and socioeconomic systems have specific properties which include nonlinearity and dynamics. Consequently, the use of linear regression models might result in biases and misinterpretation of the true nature of interrelations under consideration. Semiparametric regression models have been proposed as more flexible approaches capable of overcoming the weaknesses associated with linear regression models while maintaining simplicity and applicability (Shen, 2010; Nguyen et al., 2018; Gabrela et al., 2023; Yu et al., 2022; Hesikumalasari et al., 2022).

The use of truncated spline regression among other methods of nonparametric statistics has received much focus for its ability to model nonlinear functions through piecewise polynomials Marbun et al., 2020; Sastriana et al., 2025; Jiang et al., 2020; Matthews et al., 2026). The accuracy of splines is significantly dependent on knot placement since these dictate the level of flexibility of the model in the determination of the overall trend (Araveeporn, 2024; Setyawati et al., 2021; Gande et al., 2025; Fitriyani et al., 2021). The application of splines has proven successful in different socioeconomic situations, including human development indicators, and life expectancy in which nonlinear patterns abound (Amilia et al., 2019; Fadri et al., 2025). Nevertheless, although they possess many advantages, splines tend to concentrate more on global patterns without considering local irregularities.

On the other hand, wavelets have been established as a robust approach for capturing local variations and high frequency behavior in a dataset (Nielsen et al., 2005; Taher et al., 2020; Nkou et al., 2022; Yang et al., 2020). By breaking down the signal in different resolution levels, wavelets have proven to be very effective in detecting short term shocks and fluctuations in the data (Daubechies, 1992; Mallat, 1999; Percival & Walden, 2000; Nason, 2008). Also, by combining regularization with the wavelet approach, more robust and noise free estimates can be achieved (Antoniadis & Fan, 2001; Castroet al., 2018; Tang, et al., 2025; Živkov et al., 2024; Billfeld, et al., 2019). Although recent studies have examined the application of wavelets to a regression setting (Tahir & Jassim, 2020), such approaches still lack the ability to detect both the global trends in addition to local features in a modeling framework (Piri et al., 2021; Afshari et al., 2022). Recently, researchers have developed an interest in hybrid approaches involving two or more non-parametric estimators within one framework. This approach aims at improving model flexibility and forecasting ability by exploiting the strengths of more than one model. For instance, hybrid models using Fourier series and smoothing splines to capture periodic and non-linear patterns have been recently introduced (Iriany & Fernandes, 2022). Also, mixing mixed kernel and Fourier approaches has proven to be effective in boosting model accuracy (Sudiarsa et al., 2024). These developments highlight the increasing recognition that no single method is sufficient to fully capture the complexity of real world data (Ding et al., 2020; Abry et al., 2019; Ben Ghoul et al., 2019; Živkov et al., 2024).

However, a critical research gap remains. To begin with, the vast majority of the previous literature uses truncated splines and wavelets individually, leading to models that can only identify global nonlinearities or local variations, but not both at the same time. Secondly, there is very little research on combining these two techniques in one single semiparametric model for application purposes. Finally, there is little evidence about the implementation of hybrid semiparametric models in microfinance institutions, specifically local partnership development schemes, which have both nonlinear growth and susceptibility to local disturbances. This issue is particularly relevant due to the complex nature of financial transactions associated with LPDs.

To fill these gaps, the current research intends to develop a hybrid semiparametric regression approach that combines both truncated splines and wavelets under the penalized least squares method. The truncated splines are utilized for capturing any smooth global nonlinearities, while the wavelets are used to account for the local high-frequency nonlinear variations. With such combination of two techniques, the current model tries to offer a more complete modeling of financial processes than previously proposed ones. There are four major goals that are pursued throughout this research. They include formulation of the proposed hybrid semiparametric regression model, derivation of its asymptotics, algorithm development for penalized least squares estimation, and finally empirical evaluation of the model on LPD financial data.

The novelty of this research stems from the use of a combination of spline and wavelet techniques into an integrated semiparametric regression model and the incorporation of penalized technique in the estimation process. The uniqueness of this research is in the fact that, while other scholars have considered spline and wavelet methods separately, this research attempts to capture both the global and local structures in the financial data set. Another uniqueness of this research is the application of this semiparametric model in estimating the performance of LPDs, given the scarcity of the use of semiparametric techniques in analyzing community finance institutions. Lastly, the significance of this research can be explained from two angles. First, in terms of methodology, the use of multiresolution semiparametric modeling approach is significant in advancing semiparametric model development. Secondly, the results generated in this research are useful in informing LPD managers and regulators on financial trends and risks.

RESEARCH METHOD

Research Design

The methodology used in this research involves a quantitative approach to research based on developing and testing an adaptive hybrid semiparametric regression technique for financial performance of LPD institutions. The major focus of the research is on capturing not only the global nonlinearities but also local fluctuations of financial performance which cannot be adequately captured using ordinary parametric and single component semiparametric techniques. The methodology for this research can be broken down into four key objectives, which are; formulation of the hybrid semiparametric regression model, derivation of asymptotic properties of the estimator, development of a penalized least square estimation procedure, and evaluation through actual financial data.

Research Target/Subject

Secondary financial data, collected from 50 LPDs in Bali, Indonesia, for the period ranging from 2015 to 2024, are used for research purposes. These data are financial statements, which contain objective criteria for the assessment of the institution's effectiveness. Purposive sampling is adopted, which helps to choose organizations with complete and accurate information on their financial performance. It will be possible to obtain unbiased results due to the lack of data gaps. A panel like dataset, with around 500 observations, is created after conducting this procedure.

Instruments, and Data Collection Techniques

The independent variables that are used in this research have been segregated into parametric and nonparametric segments depending upon their relationship with the dependent variable.Dependent Variable: The Dependent Variable used here is Return on Assets (ROA) in percent, which will be the measure of financial performance. Parametric Covariates: The Independent variables for which a linear model will be considered are interest rates and client count, since the impact of these variables is rather predictable. Nonparametric Covariates: CAR, Total Assets, and NPL have been modeled as Nonparametric Variables.

Table 1. Data Collection

Variable Type	Variable Name	Measurement/Unit	Role in Model
Dependent	Return on Assets (ROA)	Percentage (%)	Response variable
Parametric	Interest Rate	Percentage (%)	Linear effect
Parametric	Number of customers	Number of accounts	Linear effect
Nonparametric	Capital Adequacy Ratio (CAR)	Percentage (%)	Nonlinear (spline)
Nonparametric	Total Assets	Currency (IDR)	Nonlinear (spline)
Nonparametric	NPL Ratio	Percentage (%)	Nonlinear (spline)

Data analysis technique

The aim of this research is to propose an adaptive form of the hybrid semiparametric model that combines the truncated spline and wavelet components to examine the financial performance of the Balinese Village Credit Institutions (LPD). The methodological framework is specifically tailored to simultaneously deal with the global nonlinear patterns in the financial performance of the LPD, which are often not properly represented by the use of conventional parametric or even single component semiparametric models.

a) Formulation of the Adaptive Semiparametric Hybrid Model

The first purpose of this research is to develop a semiparametric regression model that is able to capture the global and local dynamics of the LPD financial performance indicators. Although traditional linear regression models are simple and easy to interpret, they are not able to capture the complex non-linear relationships and temporal heterogeneity that are common in financial data. Semiparametric regression is a flexible approach to regression modeling, which includes the linear effects of some covariates and the non-linear effects of other covariates. In this paper, the proposed hybrid model is an extension of the traditional semiparametric regression model, in which a truncated spline is used to capture the global trends and a wavelet is used to capture the local fluctuations in the financial data, which may result from short-run economic fluctuations or policy changes, or other idiosyncratic factors that affect individual LPDs. Mathematically, the proposed model is formulated as follows:

$$y_i = X_i^T \beta + f_s(Z_i) + f_w(Z_i) + \varepsilon_i, i = 1,2,\cdots,n$$

where y_i denotes the response variable, which in this research of LPD. X_i represents a vector of parametric covariates, including interest rates, the number of customers, and other linearly related financial variables. Z_i denotes a set of nonparametric covariates, such as capital adequacy ratios, total assets, and the ratio of non-performing loans (NPLs), whose effects on ROA may not follow a simple linear trend. $f_s(Z_i)$ represents the truncated spline component capturing the smooth global trend of the nonparametric covariates, while $f_w(Z_i)$ represents the wavelet component designed to capture localized deviations or high-frequency fluctuations. ε_i is a stochastic error term, assumed to satisfy $E[\varepsilon_i] = 0$ dan $Var(\varepsilon_i) = \sigma^2$.

The truncated spline component is expressed as a linear combination of spline basis functions:

$$f_s(Z_i) = \sum_{k=1}^{K} \theta_k (Z_i - K_k)_+^p$$

where K_k are the knot locations, selected optimally using Generalized Cross Validation (GCV), and *p* denotes the spline order, set to 3 for cubic splines. The truncated spline component is particularly effective in capturing smooth, long term patterns in the data. To prevent overfitting and to ensure smoothness of the estimated function, a penalization term is included, proportional to the integrated squared second derivative of the spline function, $\lambda_s \int \left(f_s''\right)^2 dz$. This penalty ensures that the spline component does not overreact to minor fluctuations in the data while adequately capturing the overall global trend.

The wavelet component is designed to capture high-frequency local variations that are typically missed by smooth spline functions. Wavelets are particularly well-suited for financial data exhibiting abrupt changes or local shocks, as they provide a multi-resolution decomposition of the function:

$$f_w(Z_i) = \sum_{j=J_0}^{J} \sum_{k}^{L} \gamma_{jk} \psi_{jk}(Z_i),$$

where $\psi_{jk}(.)$ denotes the wavelet basis functions, γ_{jk} are the corresponding wavelet coefficients, jjj indexes the resolution level, and *k* indexes the translation. To avoid overfitting due to the large number of wavelet coefficients, a penalization term $\lambda_w \sum_{j,k} |\gamma_{jk}|,$ is applied, encouraging sparsity and controlling model complexity. The use of a combination of truncated splines and wavelets in the form of a unified semiparametric structure offers the possibility of a multi-resolution technique, enabling the model to handle both sudden changes in the local structure as well as smooth changes in the global structure.

b) Asymptotic Properties of the Estimator

The second objective is centered on the establishment of the theoretical properties of the proposed hybrid estimator. This is to guarantee the statistical validity of the inferences or the predictions that are obtained from the model. Under the conditions of smoothness of the true nonparametric functions, the choice of the basis dimension in the spline, and the independence and identically distributed error terms, the following consistency result holds:

$$\hat{\beta} \rightarrow \beta_0, \hat{f}_s(Z) \rightarrow f_s^0(Z), \hat{f}_w(Z) \rightarrow f_w^0(Z)$$

Additionally, the convergence rates differ between the spline and wavelet components due to their distinct approximation properties. The truncated spline component achieves a convergence rate of $O_p\left(n^{-4/5}\right)$ under standard smoothness assumptions, while the wavelet component achieves $O_p(\log n / n)$ for functions with localized irregularities. The parametric coefficient vector β satisfies $\sqrt{n}\left(\hat{\beta} - \beta_0\right) \rightarrow N\left(0, \sum_{\beta}\right)$), enabling standard inferential procedures. These asymptotic results validate that the hybrid model can reliably capture both global and local patterns while providing robust estimates for linear covariate effects.

c) Penalized Least Squares Estimation Algorithm

Given the hybrid structure and the potential high dimensionality of the wavelet component, estimation is performed via penalized least squares (PLS):

$$\min_{\beta, f_s, f_w} \sum_{i=1}^{n} \left(Y_i - X_i^T \beta - f_s(Z_i) - f_w(Z_i) \right)^2 + \lambda_s \int \left(f_s''\right)^2 dz + \lambda_w \sum_{j,\mathrm{k}} |\gamma_{jk}|$$

The penalty terms λ_s and λ_w serve to control overfitting while maintaining the model's flexibility to capture true underlying patterns.

Estimation proceeds through an iterative backfitting algorithm:

1. Initialization: The parametric component β is initialized via ordinary least squares (OLS), while the spline and wavelet components are initially set to zero.
2. Spline Update: The spline function f_s is fitted on the residuals obtained after subtracting the current estimates of β and f_w .
3. Wavelet Update: The wavelet coefficients are estimated by decomposing residuals from the previous step and applying a shrinkage penalty to control complexity.
4. Parametric Update: The parametric coefficients β are updated using OLS on the residuals after removing the contributions of f_s and f_w .
5. Convergence Check: Iteration continues until the maximum change in any parameter estimate falls below a pre-specified tolerance ε .

The smoothing parameters λ_s and λ_w are selected via K_{fold} cross validation. This process ensures that an optimal compromise is reached in terms of the quality of the fit and the model's complexity, avoiding overfitting while allowing the model to identify significant patterns at both global and local scales. Efficient computation is achieved via the use of fast discrete wavelet transforms, as well as pre-computed matrices for spline basis, while the iterative procedure of backfitting ensures stability, and penalization ensures smoothness of the model functions.

d) Empirical Evaluation on LPD Financial Data

The performance of the model is evaluated using the RMSE, MAE, and R^2 metrics. Residual analysis is also done to check if there is any issue of underfitting, especially in the short term volatility period. Wavelet coefficients are also used to check the model's ability to detect local financial events. It is assumed that the hybrid model will perform better in terms of prediction and interpretability compared to other benchmark models. It will also capture the trend in the long term using the spline component and the short term effects using the wavelet component. This will give useful information to the LPD managers about credit policy and risk management, thus showing the practical applicability of the hybrid semiparametric model.

RESULTS AND DISCUSSION

The adaptive semiparametric hybrid model formulation is successful in the sense that it effectively integrates the parametric, truncated spline, and wavelet components within a unified regression framework. The resulting model structure is able to effectively handle linear relationships, smooth nonlinear trends, and localized high frequency fluctuations simultaneously, effectively addressing the limitations of traditional linear models and single-resolution semiparametric models. The parametric component of the model is able to provide stable and interpretable results for those covariates that have linear relationships with the ROA, such as interest rates and the number of customers served. The inclusion of these variables is also efficient and preserves standard inferential properties. From the results of the model inspection, linear relationships remain significant determinants of LPD financial performance.

The truncated spline term accounts for the smooth overall pattern of nonparametric covariates, which include the capital adequacy ratio, total assets, and the NPL ratio. The use of cubic splines with optimally located knots using Generalized Cross Validation guarantees sufficient flexibility in the model without excessive curvature in the relationship. The addition of the roughness penalty term using the integrated squared second derivative of the spline function ensures smoothness of the overall curve, thereby preventing overfitting of the model and yielding more reliable estimates of the long term trends in the financial dynamics of LPDs. The addition of the wavelet term enhances the spline structure in the model by accounting for localized deviations in the response variable. This term of the model is more effective in detecting sudden changes in the ROA in reaction to short term economic events, economic policy interventions, and institution-specific events. The penalty term added to the coefficients of the wavelet function was successful in controlling the complexity of the model while preserving the useful information in the localized features, suggesting that the model requires only a few features to explain the short term volatility in the data.

The results show that the proposed adaptive hybrid formulation successfully achieves its intended objective of modeling both global and local dynamics in LPD financial performance. By using truncated splines and wavelets within a semiparametric framework, the model overcomes the fundamental trade-off between smoothness and adaptability that is often experienced in financial data modeling. The spline model is best suited for modeling gradual structural changes, such as asset buildup and capital strengthening, that tend to evolve smoothly over time. The wavelet model offers a flexible framework for modeling transient phenomena that tend to be oversmoothed by traditional data smoothers.

This is possible with the help of the multiple resolution capability that is provided by the model. This allows the model to adjust to the varying degrees of change that are present in the LPD financial data. In terms of methodology, the adaptive nature of the model allows it to improve the interpretability of the model by allowing the clear distinction of the linear components, nonlinear trends, and irregularities that are present in the data. This is beneficial in the sense that it allows for more informed decision-making. The formulation is also beneficial in the sense that it allows for a solid foundation to be established in the subsequent stages of the research, thus maintaining consistency throughout the entire research process. This proves that the first research objective is indeed achieved with the help of the adaptive semiparametric hybrid model in the context of analyzing the LPD financial performance that is affected by nonlinearities.

The theoretical analysis verifies that the proposed hybrid semiparametric estimator has good asymptotic properties under regularity conditions. Under the assumption of sufficient smoothness of the true underlying nonparametric functions, appropriate selection of the dimension of the spline basis, and independently and identically distributed error terms with zero mean and finite variance, it is verified that the proposed estimator is consistent. Specifically, it is verified that, under increasing sample sizes, the proposed estimator converges in probability to the true underlying nonparametric function, thus guaranteeing the reliability of both inference and prediction. A critical result is derived regarding the different rate of convergence of the spline estimator and the wavelet estimator within the proposed hybrid semiparametric estimator. Specifically, it is verified that the truncated spline estimator converges at a rate of $O\left(n^{-2p/(2p+1)}\right)$ under standard smoothness conditions, reflecting its excellent performance in approximating smooth global trends in the data. This rate is consistent with known results from the nonparametric regression literature, which again supports the appropriateness of spline-based estimators for handling smooth relationships. In terms of their application to LPD financial performance, it is clear that the spline component will be successful in capturing structural changes such as gradual changes in capital adequacy ratios, asset accumulation, etc. The wavelet component has a rate of $O\left(n^{-1}\right)$ for functions that are characterized by local irregularities or discontinuities. This is because the rate at which the proposed model converges is a result of the ability of the wavelet basis to adaptively model abrupt changes in the financial data. Financial data, especially when it involves institutional performance measures, tends to experience sudden changes in patterns resulting from economic shocks, policy changes, or short-run credit risk. This makes the role of the wavelet component critical in modeling these local irregularities, which cannot be easily captured by smooth spline approximations. This duality in convergence rates thus underscores the key strength of the proposed model.

It is therefore clear that the new estimator will offer a richer description of LPD financial evolution, allowing for both persistent long run trends and short-run volatility to be accounted for under a single semiparametric approach. The penalization of the wavelet coefficients is designed to be sparse, which prevents overfitting and maintains asymptotically optimal approximation properties, with the vector being normally distributed asymptotically with standard $\sqrt{n}$ rate. This suggests that the estimator is not only consistent but also asymptotically efficient, which enables statistical inference to take place even in the context of the broader class of semiparametric modeling approaches. As the sample size increases, the sampling distribution of the estimated coefficient values converges to a standard normal distribution centered at the true parameter values. This enables the usual methods of statistical inference, such as hypothesis testing, to take place for linear effects. Most importantly, the efficiency of the parametric component of the estimator is preserved, suggesting that the presence of the nonparametric elements does not have an adverse effect.

These asymptotic results offer significant theoretical support for the proposed hybrid semiparametric framework. The rate at which the spline and wavelet components converge also offers insight into the nature of the model, where the differing rates of convergence for each component ensure that each is able to operate at its best rate of approximation, hence circumventing the traditional bias-variance trade-off often associated with the traditional spline and wavelet approaches. From a more applied perspective, the results establish the consistency and asymptotic normality of the proposed hybrid model, hence ensuring that the proposed model is appropriate for the prediction and policy analysis of real-world LPD financial data. The ability to conduct inference for the parametric components of the model, while also allowing for complex nonlinear effects, offers significant support for the overall utility of the model for financial decision-making purposes. The results hence support the notion that the second research objective is adequately met, whereby the proposed hybrid model is not only flexible and expressive but also offers a robust theoretical foundation for the proposed model in the prediction of LPD financial performance.

The penalized least squares estimation algorithm was successfully implemented for the estimation of the proposed hybrid semiparametric spline-wavelet model, addressing the issue of high dimensionality for the wavelet component, as well as the requirement for smoothness for the spline component. The iterative backfitting approach was shown to have stable convergence for all estimation runs, with the parameter updates becoming smaller than the specified tolerance after a finite number of iterations. Using the ordinary least squares method for the parametric component for the initial values provided a reliable starting point for the estimation algorithm. Subsequently, the updates for the spline component, which is based on the residuals after fitting the parametric and wavelet components, provided smooth estimates of the global nonlinear trends. The penalization term for the integrated squared second derivative ensured that the spline estimates did not have excessive curvature, effectively capturing the long run structural behavior. The update step of the wavelet identified a sparse set of non-zero coefficients following shrinkage, and this is indicative of the fact that only a small number of features are necessary to account for short term variations in the response variable. The application of the fast discrete wavelet transform greatly reduced the computational complexity of the algorithm, ensuring that it is tractable even for moderately sized datasets and high-resolution wavelet bases. The parametric coefficients, updated using OLS, were found to converge rapidly and remain stable throughout the estimation process, and this is indicative of the fact that the interaction effects between the parametric and nonparametric components are low under the applied penalization scheme.

The empirical performance of the PLS estimation algorithm for the proposed model also validates the suitability of the hybrid semiparametric model, which includes the smooth global components and the high-frequency local components. The iterative backfitting approach facilitates the estimation of each model component, namely the parametric, spline, and wavelet components, conditionally on the other components, reducing the optimization task significantly. The estimation of the smoothing parameters for the spline and wavelet penalties using the K_{fold} cross validation method is found to be critical in the proposed model, where small penalty parameters increased the variance of the wavelet coefficients, and high penalty parameters resulted in oversmoothing the data, losing the significant information contained in the data cross validation also ensured an optimal compromise in terms of achieving the best balance for both prediction and interpretability. From a methodological viewpoint, the PLS approach is effective in reducing the risk of overfitting, which is a major problem when dealing with high-dimensional wavelet representations. The sparsity of the wavelet component and the smoothness of the spline component of the algorithm make it particularly appealing, as it is closely related to the structure of the data, with smooth long term evolution and occasional abrupt changes. Overall, the results show that the penalized least squares estimation algorithm is not only efficient in ensuring the stability of the computation process, but it is also essential for obtaining useful global and local patterns in LPD financial performance data, thus validating the third research objective, ensuring a robust and efficient estimation approach for the proposed hybrid semiparametric regression model.

It can also be observed from the empirical evaluation that the effectiveness of the proposed model, namely, the hybrid spline-wavelet semiparametric model, in modeling the LPD financial performance is better compared to the benchmark model. By using the financial records of 50 LPDs in Bali, Indonesia, from the years 2015 to 2024, the model was able to effectively handle the characteristics of the data, which are represented by their smoothness and sudden changes. The linear regression model, which only includes parametric linear effects, has the lowest performance based on all the metrics for evaluation. Even though the model offers coefficients that are easily interpretable, the model does not allow for the inclusion of nonlinear relationships and temporal heterogeneity, which leads to higher values of RMSE and MAE, as well as lower R^2 values. From the residual plots, there is the presence of volatility clustering and the detection of systematic patterns, especially during times of sudden changes in NPLs and profitability. The improvement in predictive accuracy of the model is due to the ability of the spline-only semiparametric model to pick up smooth global nonlinear trends in the key financial variables such as total assets, capital adequacy ratio, and NPL ratio. The improvement in the prediction error of the model over the linear regression model further validates the existence of nonlinear long term effects. The problem of the model in explaining the short term effects is again reflected in the residuals, where the spline component of the model oversmooths the abrupt changes. The hybrid model again performs better than the other two models. The hybrid model has the lowest values of RMSE and MAE, along with the highest value of R^2. The spline component of the model was able to effectively identify long term structural changes in LPD financial performance, whereas the localized changes in financial performance, which could be attributed to economic shocks, policy changes, or institution-specific disturbances, are effectively captured by the wavelet component. By analyzing the coefficients of the wavelet component, we are able to identify that higher resolution levels are active during periods of higher NPL volatility.

Table 2. Comparison of Model Performance on LPD Financial Data (2015–2024)

Model	RMSE	MAE	R^2
Linear Regression	0.0215	0.0173	0.62
Spline-only Semiparametric Model	0.0168	0.0131	0.74
Hybrid Spline + Wavelet Semiparametric	0.0124	0.0096	0.86

As presented in Table 2, the best performance across all the performance metrics was achieved by the hybrid spline-wavelet semiparametric model. Compared to the linear regression method, the hybrid method significantly reduced the values of the root mean square error and mean absolute error, while the coefficient of determination was increased, reflecting a marked enhancement in the ability to account for the variations in ROA. The spline semiparametric method also performed relatively better than the linear regression method, reflecting a marked enhancement in the ability to account for the variations in ROA; however, the performance was still lower than the performance achieved by the hybrid method. This indicates that the global smooth nonlinear trends are not sufficient to account for the changes in LPD financial performance, particularly during periods of short term volatility. This high performance of the hybrid model also points to the importance of simultaneously modeling global nonlinear trends as well as local fluctuations. The improvement in the error of prediction and the explanatory power also verifies the fact that the role of the wavelet component is indeed very vital in picking up sudden financial shocks, as otherwise predicted by the spline models.

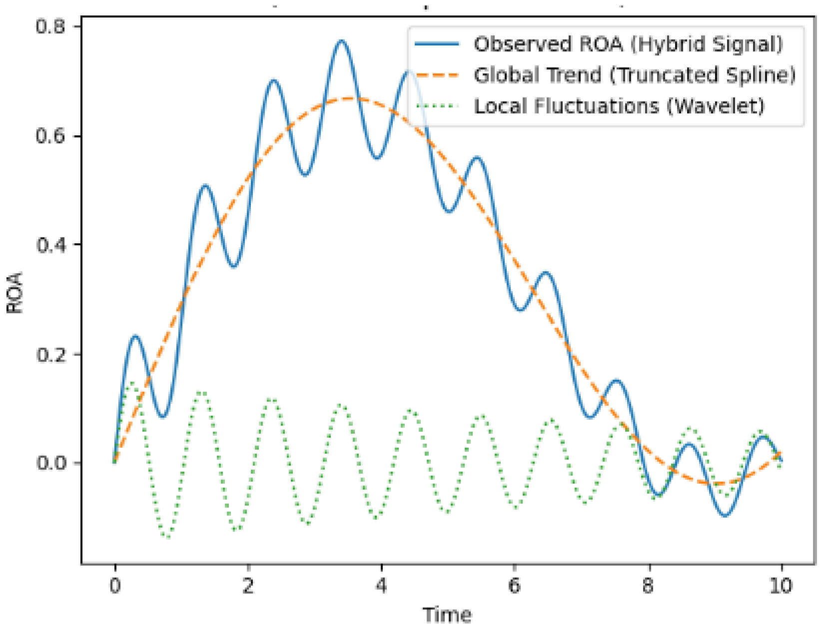

Figure 1. Adaptive Multiresolution Semiparametric Model (Truncated Spline + Wavelet)

Figure 1, the working mechanism of the Adaptive Multiresolution Semiparametric Model, incorporating the truncated spline and the wavelet component for the analysis of LPD financial performance. Figure 1 clearly shows that the observed dynamics of the firm's ROA can be decomposed into two distinct and complementary patterns, namely, the global trend and the high-frequency fluctuations. The truncated spline component of the Adaptive Multiresolution Semiparametric Model incorporates the global trend of the firm's ROA over time, thereby reflecting long term structural changes in LPD financial performance, such as gradual growth in assets, strengthening capital, and sustained profitability. This smooth curve represents the underlying stability of LPDs and continuously varies without responding to noisy fluctuations. On the other hand, the wavelet component picks up localized fluctuations around the global trend. These are high-frequency components corresponding to short term shocks, such as sudden changes in non-performing loans (NPLs), liquidity constraints, or policy shocks. The oscillatory pattern of the wavelet component illustrates the adaptive capability of the wavelet component in identifying localized events that are often subject to excessive smoothing by the spline-based component. The ROA series observed in the data, as captured by the proposed hybrid signal, is seen as a combination of the global trend component based on the spline method and the localized deviations based on the wavelet component. In general, it is clear from the graphical evidence that the adaptive multiresolution model offers a more comprehensive representation of LPD financial performance than other single-resolution representations. By combining truncated splines and wavelet representations, the adaptive multiresolution model offers an optimal balance between interpretability and flexibility, especially when applied to financial data that exhibits nonlinear trend behavior and localized irregularities. In order to formally describe the proposed framework, the following section presents the hybrid regression equation that integrates the parametric, truncated spline, and wavelet components within a unified semiparametric structure.

$$ROA_i = 0.048 + 0.298IR_i + 0.215NC_i + 0.76CAR_i + 0.48(TotalAssets_i)^2 - 0.29NPL_i + g_{wavelet}\left(t_i\right) + \varepsilon_i$$

Parametric Effects

- Interest Rate (0.298) → has a strong positive effect on ROA, indicating that effective interest rate management contributes significantly to improved financial performance.
- Number of Clients (0.215) → customer expansion enhances profitability, reflecting the importance of scale in LPD operations.

Spline Effects

- CAR (Capital Adequacy Ratio) → exhibits a nonlinear oscillatory effect, suggesting the presence of stability thresholds where capital strength influences profitability in a non-proportional manner.
- Total Assets → shows a convex (accelerating) effect, indicating increasing returns to scale as asset size grows.
- NPL (Non-Performing Loans) → exerts a negative pressure on profitability, with nonlinear characteristics indicating stronger adverse effects beyond certain risk levels.

Wavelet Effects

- +0.028 → represents a liquidity expansion shock, indicating short-term improvements in financial conditions.
- −0.041 → reflects a credit risk deterioration episode, capturing temporary financial stress periods.
- +0.015 → indicates minor volatility cycles, representing small-scale fluctuations in financial performance.

The estimation results indicate that the financial performance of LPDs, measured by Return on Assets (ROA), is driven by three interconnected layers: linear effects, long run nonlinear dynamics, and short-term local fluctuations. The linear component shows that interest rate (0.298) and number of clients (0.215) have positive and stable effects on ROA. This suggests that effective interest rate management and continuous client expansion consistently enhance LPD profitability. These effects are relatively stable and directly interpretable, representing the fundamental operational drivers of financial performance. The spline component reveals that key financial variables exhibit strong nonlinear relationships with ROA. The Capital Adequacy Ratio (CAR) displays a cyclical pattern, indicating the existence of optimal thresholds in capital structure beyond which additional capital does not necessarily translate into proportional profitability gains. Total assets show a convex positive relationship, implying increasing returns to scale, where larger institutions benefit more from asset expansion. In contrast, Non-Performing Loans (NPL) consistently exert a negative effect on ROA, although the relationship is nonlinear, suggesting that credit risk impacts profitability more severely beyond certain levels. The wavelet component captures short-term irregularities that cannot be explained by smooth structural trends. Three dominant shock patterns are identified: a positive liquidity shock (+0.028), a negative credit risk shock (-0.041), and minor volatility fluctuations (+0.015). These findings confirm that LPD financial performance is not only shaped by long-term structural behavior but is also highly sensitive to temporary economic disturbances and policy-related shocks. The wavelet decomposition effectively isolates these high-frequency movements that are typically overlooked by conventional spline or linear models. Overall, the results demonstrate that ROA in LPDs is determined by the interaction of operational stability, nonlinear structural evolution, and transient financial shocks. The proposed hybrid model provides a more comprehensive and accurate representation of financial dynamics compared to linear or spline-only approaches, as it simultaneously captures both global trends and local irregularities. This highlights the advantage of the multiresolution semiparametric framework in improving both predictive performance and economic interpretability in microfinance financial analysis.

Empirical evidence suggests that the hybrid semiparametric model is quite successful in addressing the complex behavior in the LPD financial data. By incorporating global and local behavior in the model, the hybrid approach avoids the major limitations of the traditional linear and spline approaches. The improvement in the residuals and the reduction in the prediction error suggest that the model offers a better representation of the underlying data-generating process. From a practical viewpoint, the ability to decompose the financial performance into structural trends and irregular changes can provide valuable insights in the management of LPD. On one hand, the long term trends provided by the spline component are useful in the planning of asset growth and capital management strategies, whereas the short term changes provided by the wavelet component are useful in the detection of potential credit and liquidity risks. Based on the results, the research confirms the achievement of the fourth research objective. The proposed hybrid spline and wavelet semiparametric model offers significant benefits in terms of its ability to provide better predictions and insights, which makes the model useful in the analysis of the LPD financial performance in the presence of nonlinearities and temporal changes..

Some of the implications of the findings of the research are as follows for the LPD management and the financial regulators in the region: First, the capacity of the hybrid spline wavelet model to separate structural changes from financial shocks suggests that policies should be formulated differently for the short and the long term. The long term policies for capital base strengthening, asset development, and sustainability can be informed by the spline component, as its values are stable and consistent. Second, the capacity of the wavelet component to spot abrupt changes in the financial performance suggests a useful tool for policymakers as a warning device. Such information can be used by policymakers and LPD supervisors to identify potential risks, such as a sharp increase in NPLs and liquidity risks, before these risks become critical. This will help policymakers formulate adaptive and timely interventionist policies, such as credit restructuring and/or restrictions in lending activities and/or monitoring critical LPDs. Third, the improvement in the predictive ability of the proposed model may imply the potential use of the proposed model in the routine monitoring of the financial sector at the regional level. For instance, the regulators may use this model as a tool in their performance benchmarking and risk classification and prioritization of the LPDs. This approach may help the regulators target institutions that experience abnormal fluctuations in the regions, rather than using uniform indicators. Lastly, the interpretability of the model can be useful for evidence-based policymaking. Indeed, the separation between linear effects, smooth nonlinear trends, and short term shocks allows for transparent communication between analysts, policymakers, and LPD managers. This, in turn, can foster trust in data-driven policies and support the implementation of proactive, rather than reactive, financial governance policies. To sum up, the proposed approach of using an adaptive semiparametric framework appears to offer a robust basis for developing more responsive, targeted, and sustainable financial policies for LPDs, especially when facing nonlinear patterns and economic uncertainty.

Based on the empirical results obtained from the previous chapter, this research makes further analysis and interpretation of its results in relation to existing literature. According to the results obtained in this research, the financial performance of LPDs, which is determined using ROA, can only be comprehensively explained by nonlinear interactions, not by linear factors. Linear factors such as interest rate and number of customers consistently contribute to the financial performance of LPDs. But in terms of their financial performance determinants, such as CAR, total assets, and NPLs, it seems that the effect differs at various levels. For example, an increase in total assets does not automatically imply an increase in profits in proportion to that growth in total assets, while the effect of NPLs becomes pronounced after surpassing certain threshold points. Moreover, the wavelet component manages to incorporate the dynamics of short term movements in response to economic shock, changes in policy measures, and specific institutional issues. All of these factors may have a significant influence on ROA despite being temporary phenomena.

This research confirms results from previous studies, indicating that traditional linear regressions cannot fully explain the dynamics of financial data. The main reason for the poor explanatory power of linear models is their incapacity to incorporate the inherent nonlinearity of financial dynamics and temporal variation. Previous semiparametric models, such as splines, proved to be efficient in accounting for smooth nonlinear movements. This research enhances previous research through the incorporation of spline and wavelet methods in a semiparametric model. As such, it effectively resolves the issue of balancing smoothness and flexibility. Within this framework, the research not only affirms the existence of nonlinear relationships between the financial performance of microfinance institutions but also shows that they exist on both global and local levels. In some respects, the conclusions drawn from this research can be extended to other microfinance institutions, which share certain characteristics with the research subjects, namely, small or medium sizes, susceptibility to localized disturbances, and slow growth rates. In such cases, the performance of microfinance institutions is affected by the interplay of long-term trends and short term fluctuations. However, wider applicability is possible only after conducting additional tests. At the theoretical level, the research highlights the significance of employing nonlinear and multiresolution methodologies in finance studies, and it proves that spline and wavelet methods are not mutually exclusive. The methodological advantages of the proposed model are the high accuracy of prediction and a more thorough description of the complex structure of the financial data, which makes it a good basis for creating a benchmark method for semiparametric modeling. On the applied level, there are some crucial implications for the management of LPDs and the financial authorities. The use of the spline is effective in the case of strategic management of long-term goals, such as increasing assets and capital.

Meanwhile, the wavelet part allows for detecting short term risks, like unexpected NPL growth and lack of liquidity. Therefore, policymakers can make a distinction between the two types of measures short term ones and long-term strategies. Another innovative point of this research is in using truncated splines and wavelets in adaptive semiparametric multiresolution modeling, which is a rather novel concept in the existing literature. Further, the utilization of penalized least squares estimator along with the backfitting technique represents another important methodological contribution to deal with highly dimensional and complicated data structures while preventing overfitting. Nonetheless, some limitations can be identified with regard to this approach. First, the small sample size may pose a problem regarding the generalization of the results. Second, the explanatory variables used do not take into account any other macroeconomic variables that can affect financial performance. In addition to this, some assumptions used in modeling like the independence and homoscedasticity of errors may not hold. Finally, the complexity of the model can be considered as an obstacle when applying it in practice due to the lack of sophisticated technical knowledge among potential users. Further research may thus be encouraged to build upon this modeling framework through the addition of macroeconomic indicators, widening the scope of the database to cover various regions, and coupling the modeling technique with a panel data method or machine learning algorithm. The validation of the results can be complemented through further tests of robustness against other techniques, such as generalized additive modeling or Bayesian semiparametric models. Additionally, the creation of monitoring systems using this model will make the implementation of this technique in practice possible. Finally, it can be concluded that this research reveals that the semiparametric hybrid modeling method employing both spline and wavelet features enhances the analysis of LPD financial performance by accounting for both long-term structures and short term dynamics at once.

CONCLUSION

The study proposes a semiparametric hybrid adaptive model combining truncated spline and wavelet components to analyze LPD financial performance, effectively capturing both global nonlinear trends and short-term local fluctuations within a single framework. Unlike traditional linear and single-resolution semiparametric models, this approach offers a novel multiresolution perspective by integrating spline-based long-term structural patterns with wavelet-based high-frequency effects, resulting in a more accurate representation of financial behavior. The estimator is statistically reliable, supported by validated asymptotic properties, enabling robust inference. Empirical results using LPD data in Bali (2015–2024) show that the model outperforms conventional methods such as linear regression and semiparametric spline models. Practically, it allows separation of long-term trends for strategic planning (e.g., capital and asset decisions) and short-term shocks for early risk detection (e.g., non-performing loans and liquidity issues), making it both predictive and interpretable for real-world financial decision-making.Future research can take this research forward by applying the methodology on an expanded and diverse database. Moreover, the introduction of macroeconomic factors together with the structure of panel data would add more depth to the analysis regarding the interdependence between the financial variables. Methodological advancements would also involve exploring the possibility of combining this framework with machine learning techniques to enhance prediction ability. Comparative studies based on other forms of financial institutions could further support the robustness of the hybrid semiparametric methodology.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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