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Article

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Cogent Economics & Finance

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Suggested Citation: Rafie, Fatima-Ezzahra; Lekhal, Mostafa (2024) : Public external debt sustainability assessment: towards a machine learning based approach, Cogent Economics & Finance, ISSN 2332-2039, Taylor & Francis, Abingdon, Vol. 12, Iss. 1, pp. 1-17, https://doi.org/10.1080/23322039.2024.2429770

Cogent Economics & Finance

ISSN: 2332-2039 (Online) Journal homepage: www.tandfonline.com/journals/oaef20

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To cite this article: Fatima-Ezzahra Rafie & Mostafa Lekhal (2024) Public external debt sustainability assessment: towards a machine learning based approach, Cogent Economics & Finance, 12:1, 2429770, DOI: 10.1080/23322039.2024.2429770

To link to this article: https://doi.org/10.1080/23322039.2024.2429770

COGENT ECONOMICS & FINANCE
2024, VOL. 12, NO. 1, 2429770
https://doi.org/10.1080/23322039.2024.2429770

ECONOMETRICS & DATA ANALYTICS | RESEARCH ARTICLE

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Public external debt sustainability assessment: towards a machine learning based approach

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ABSTRACT

This study addresses the challenge of sovereign external debt sustainability by employing a cointegration test, machine-learning classifiers, and explainable models. Focusing on 22 middle-income countries during the period 2000-2021, our study aims to provide accurate insights into debt positions and capture the complex dynamics between a set of economic and fiscal indicators. Unlike conventional econometric methods, which categorize debt situations as either sustainable or unsustainable over specific periods and often have limitations in generalizing the influences of public policies on debt positions, our machine-learning approach reveals a more nuanced perspective. The results indicate that some countries have encountered episodes of debt unsustainability. These results underscore the substantial role of macroeconomic indicators in shaping a country's financial position in conjunction with outstanding debt. Furthermore, our findings demonstrate that the impact of each feature varies based on its specific threshold, emphasizing the critical role of exchange rates in straining debt sustainability.

IMPACT STATEMENT

This paper redefines sovereign debt sustainability analysis for middle-income countries by applying machine-learning techniques to reveal the influence of key economic indicators, including exchange rates, inflation, GDP growth, and foreign reserves. The findings demonstrate that debt sustainability is shaped by complex interactions between macroeconomic factors rather than debt outstanding, offering policymakers a practical framework to assess debt position with greater accuracy.

ARTICLE HISTORY
Received 8 April 2024
Revised 26 September 2024
Accepted 10 November 2024

KEYWORDS
Public external debt sustainability; intertemporal budget constraint; public policies; machine learning

SUBJECT CLASSIFICATION CODES
C38; C88; F31; F34

SUBJECTS
Development Economics; Public Finance; Machine Learning - Design; Artificial Intelligence; Economics

1. Introduction

The contemporary global economic landscape is characterized by uncertainty, extreme volatility, and lack of visibility. In response, both developed and developing countries tend to increasingly accumulate public external debt to enhance their growth and strengthen their economies' resilience. However, the lack of sound macroeconomic policies and an effective debt management strategy can lead to financial distress, thus placing sovereign external debt sustainability as a foremost concern for public authorities and global financial system regulators, given that the economic dependencies across world countries are intensified. Therefore, the financial instability of one country may negatively influence the stability of other economies or the stability of the entire international system.

According to the International Monetary Fund (2013), the sustainability of foreign borrowing is met when the country can ensure both financing of its policy goals and debt service. The IMF approach for gauging the sustainability of external debt is based on the satisfaction of liquidity and solvency conditions. Thus, debt burden is measured by the following indicators: debt stock to GDP, debt stock to exports, debt service to exports, debt stock to government revenues, or debt service to revenues. Following this approach, the

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/23322039.2024.2429770.

assessment must be prospective, examining these indicators within both baseline and stress tests, and it may also include other indicators to capture external solvency and liquidity, in addition to solvency and rollover risks. In the same line, Teică (2012) argues that to ensure debt long-run viability, the debtor must be liquid and solvent as to be able to service debt at any time, and this can be realized through a combination of efficient monetary, fiscal, and budgetary policies. Zettelmeyer (2022) defined a situation of unsustainability as a period when the repayment of debt necessarily leads to default, restructuring, or hyperinflation. Zenios et al. (2021) link debt sustainability to the optimization of the issued debt maturities. According to their findings, optimizing the financing strategy strengthens debt dynamics and ensures sustainability.

Several studies propose empirical approaches to evaluate countries' debt positions based on the verification of the long-run solvability constraint through the analysis of the stationarity of debt indicator time series (Wilcox, 1989; Hamilton & Flavin, 1986). Trehan and Walsh (1988, 1991) demonstrate that sustainability is proved through the stationarity of the linear composition of borrowing stock and net interest deficit, or inclusive of interest deficit. The authors also confirm that debt is sustainable if government expenditure, inclusive of interest, and its revenues are cointegrated. Hakkio and Rush (1991) show that the cointegration of government expenditures, inclusive of interest and revenues, as well as the stationarity of the expected real rate, prove a sustainable position. Another study, which combines unit root tests and cointegration tests between exports and imports or between exports and external debt, was conducted by Leachman and Francis (2000), who argue that foreign borrowing is sustainable if it is cointegrated with exports. Bohn (1995, 1998) criticized the reliance on stationarity tests to evaluate the debt position. Accordingly, the assessment must be based on the positive response of primary surplus to debt as a share of GDP. Thus, the budget intertemporal constraint is satisfied when the primary surplus increases as the stock of borrowed funds increases. Navarro-Ortiz and Sapena (2020) developed a probabilistic approach to evaluate debt long-run viability based on a probability distribution for the foreign repayment capacity of economies.

The multitude of these approaches demonstrate the focus of both economic-financial theoreticians and practitioners on providing an accurate framework of public external debt sustainability, by proposing different methodological models and including different variables and indicators that are likely to impact the economies' ability to repay. However, the conventional (econometric) models were designed to analyze the sustainability of public indebtedness of developed economies, particularly the United States. Similarly, the 'Debt Sustainability Assessment (DSA)' approach developed by the International Monetary fund and the World Bank, though sophisticated, has results whose validity is limited to the model's assumptions, because future is unknown, as noted by Wyplosz (2005). For instance, Bouabdallah et al. (2017) present an adjusted DSA to the context of European countries, aligning the IMF (2013) framework to the EU fiscal governance framework requirements. The adjusted approach defines solvency condition considering longer maturities instead of medium-term (five years) maturities, and assesses liquidity based on the ability to maintain the access to financial markets. Another difference in Bouabdallah et al. (2017) adjusted framework is the focus on the 'willingness to pay' in addition to the 'ability to pay'.

The DSA approach primarily concerns low-income countries, raises concerns about these methods' predictability and their suitability to the context of middle-income countries. Indeed, the resilience of the economies, the soundness of their public policies and the structure of public external debt differs across countries income categories, especially, in terms of maturity, currency of denomination and interest rates, thus making it difficult to consider a common indicator or the same level of indebtedness for all countries. The study conducted by Mendoza and Ostry (2008) provides an evidence of the divergence of the extent of the primary surplus to debt between developed economies and emerging markets. Some approaches link public debt long-run viability to the size of foreign borrowing (see Owusu et al., 2023), which may not reflect the real world since the level of indebtedness overreaches the limit of 100% as a share of GDP in many developed countries and still qualifies as sustainable, while it is considered unsustainable in countries within a cross-border borrowing outstanding that does not exceed the level of 40% as a share of GDP.

Debrun et al. (2019) shed the light on other limit of the econometric models in assessing public debt sustainability demonstrating that even though econometric analyses can be highly informative, they cannot solely guide practitioners, as they fail to convincingly determine whether a country's current public debt is likely to be serviced now and in the future.

These limits of econometric models do not concern only debt sustainability assessment, but it affects the reliability of all analysis of economic issues, and this is due to the complexity of the real economic-financial landscape. To overcome these limits, researchers and practitioners are using alternatively Artificial Intelligence (AI) Tools and these models have demonstrated higher performance than conventional methods. Nazareth and Ramana Reddy (2023) presented the applications of Artificial intelligence techniques in different financial domains namely, stock markets, portfolio management, cryptocurrency, forex markets, financial crises, sovereign defaults, and credit default swaps, and have proven an effective performance. Among the studies that used machine learning in the domain of debt management, the study conducted by Alaminos et al. (2021) to predict sovereign debt and currency crises through the application of different machine learning methods and the analysis carried out by Ma et al. (2018) to predict loan default. Zarkova et al. (2023) used random forest regression to analyze the mid-term effects of public indebtedness on macroeconomic, fiscal, monetary, global, and convergence indicators. Bussmann et al. (2021) and Chen (2021), among others, have assessed debt risk using machine learning algorithms.

Assessing public debt sustainability is a critical challenge for policymakers, particularly in middle-income countries. To the best of our knowledge, artificial intelligence has not yet been applied to public debt sustainability assessment. Our study is to propose a new framework of sovereign cross-border sustainability assessment, not to replace conventional methods, but to enhance the evaluation of sustainability, especially in the context of middle-income countries. This work contributes to the ongoing debate on sovereign debt sustainability, building on recent works such as Blanchard (2022) and Zenios et al. (2021), which highlight the importance of incorporating risk measures into debt sustainability frameworks. While our model aligns with these contributions, it diverges in its approach by maintaining the use of conventional methods, based adherence to intertemporal budget constraints.

Blanchard (2022) argues that 'assessing debt sustainability is as much art as it is science'. Conventional methods, like the seminal work by Hamilton and Flavin (1986) rely on the stationarity of time series to assess debt sustainability. Their methodology revolves around testing whether a government's debt to GDP ratio follows a stationary process, implying that the debt will not explode over time and is therefore sustainable. However, Hénin and Fève (1998) highlight significant limitations in this analysis. One key limitation is the short duration of available time series data, which can undermine the reliability of stationarity tests. This limitation arises because short time series may not capture the long-term dynamics and structural breaks that characterize economic processes. Consequently, relying solely on these tests can lead to incorrect conclusions about debt sustainability.

In response to these limitations, our study leverages machine learning techniques to provide a more robust assessment. Conventional methods often assume linear relationships among variables, but economic indicators influencing debt trajectory are likely to exhibit non-linear interactions. By employing methods like Random Forest Classifier (RFC) and Gradient Boosting Machine (GBM), we can handle large datasets, capture complex non-linear patterns, and the concern about short time series can be mitigated by machine learning's ability to leverage high-dimensional data and incorporate additional predictors (Breiman, 2001; Friedman, 2001). For instance, including macroeconomic indicators, fiscal and monetary policy variables can enrich the dataset and provide a more comprehensive analysis.

Moreover, Cross-validation is a technique to assess the performance of machine learning models. By partitioning the data into training and testing sets multiple times, cross-validation ensures that the model's predictions are not overfitted to a specific subset of data. This method provides a more reliable measure of the model's accuracy and generalizability (Kohavi, 1995).

Furthermore, the interpretability of our analysis using Shapely Additive Explanations (SHAP), and Local interpretable model-agnostic Explanations (LIME) ensure that the results are actionable for policymakers. Indeed, SHAP values provide a unified framework for interpreting the contribution of each predictor to the model's output (Lundberg & Lee, 2017), while LIME approximates the model locally to explain individual predictions, offering transparency and building trust in the model's decisions (Ribeiro et al., 2016).

The remainder of this paper is organized as follows. Section 2 provides an overview of the adopted methodology. Section 3 summarizes the empirical findings, and section 4 lays down the corresponding interpretations. Section 5 concludes.

Table 1. List of countries, de facto classification of exchange rate arrangements and monetary policy frameworks.

Country	De facto Exchange Rate Arrangement *(2021 AREAER)*	Monetary Policy Framework
Argentina	Crawl-like Arrangement	Other*
Azerbaijan	Stabilized Arrangement	Exchange rate anchor *(US dollar)*
Bolivia	Stabilized Arrangement	Exchange rate anchor *(US dollar)*
Egypt	Stabilized Arrangement	Exchange rate anchor *(US dollar)* - In transition towards inflation targeting
Eswatini	Conventional Peg	Exchange rate anchor *(Other)*
Fiji	Conventional Peg	Exchange rate anchor (*Composite)*
Ghana	Crawl-like Arrangement	Exchange rate anchor *(US dollar)*
Guatemala	Stabilized Arrangement	Exchange rate anchor *(US dollar)*
Haiti	Other Managed Arrangement	Other*
Honduras	Crawling Peg	Exchange rate anchor *(US dollar)*
Jordan	Conventional Peg	Exchange rate anchor *(US dollar)*
Mauritania	Crawl-like Arrangement	Other*
Morocco	Pegged exchange rate within horizontal bands	Exchange rate anchor (*Composite)*
Nepal	Conventional Peg	Exchange rate anchor *(Other)*
Nicaragua	Crawling Peg	Exchange rate anchor *(US dollar)*
Nigeria	Stabilized Arrangement	Exchange rate anchor *(US dollar)*
Philippines	Crawl-like Arrangement	Exchange rate anchor *(US dollar)*
Tajikistan	Stabilized Arrangement	Exchange rate anchor *(US dollar)* - In transition towards inflation targeting
Tanzania	Stabilized Arrangement	Exchange rate anchor *(US dollar)*
Tunisia	Crawl-like Arrangement	Other*
Vanuatu	Other Managed Arrangement	Other*
Vietnam	Crawl-like Arrangement	Exchange rate anchor *(US dollar)*

Source. Authors based on AREAER (2021).
*Countries have no explicitly stated nominal anchor, but rather monitor various indicators in conducting monetary policy.

2. Methodology

Carrera and Vergara (2012), Eichengreen et al. (2003), and Ragbi et al. (2016) shed light on the dynamic interplay between debt sustainability and exchange rate regime. In the present study, we aim to assess the sustainability of public external debt within a selected group of middle-income countries where monetary authorities intervened to stabilize the exchange rate, using annual data from 22 countries from 2000 to 2021. The list of countries included in our study, along with their respective de facto Exchange Rate Arrangements and monetary policy frameworks, is presented in Table 1. We based our selection on the availability of data and de facto classification of their exchange rate arrangements, as provided by the IMF in the 72nd issue of the Annual Report on Exchange Arrangements and Exchange Restrictions (AREAER) (International Monetary Fund, 2022).

2.1. Data

Macroeconomic policies, national social, economic, and political conditions, debt management strategies, and the international context are key factors that determine the sustainability of public external debt. These factors shape an economy's long-term ability to service debt obligations and influence its solvency. In this study, we analyze public foreign borrowing across 22 middle-income countries, incorporating eight key variables that represent the major determinants of cross-border borrowing. In addition to the external debt-to-GDP ratio, these variables capture the primary macroeconomic policies and indicators influencing sovereign debt sustainability. GDP growth, imports, and exports have a notable impact on the economy's solvability (Hamilton & Flavin, 1986) and degree of reliance on external borrowing. Debt sustainability is achieved when a country implements effective fiscal and monetary policies (Teică, 2012). In accordance with this perspective, we introduce expenditure as the fourth variable, recognizing that high government spending may pose challenges in maintaining debt at a sustainable level. In addition, to assess the impact of monetary authorities' decisions on the sustainability of public external debt in middle-income countries, we include inflation, the exchange rate, and foreign reserves.

In the second iteration of our machine learning approach, we introduce debt service as an additional variable to enhance the depth of our analysis. Debt service represents the regular repayment of both principal and interest on outstanding public external debt. It is crucial in understanding short-term fiscal pressures, as high debt service payments can constrain a country's ability to invest in essential services or infrastructure. Although not included in the initial iteration of our model, debt service is

Table 2. Explanatory variables.

Variables	Definition	Code in World Development Indicators Database
Debt service	Debt service on external debt, public and publicly guaranteed (PPG) (TDS, current US$)	DT.TDS.DPPG.CD
Exchange Rate	Official exchange rate (LCU per US$, period average)	PA.NUS.FCRF
Expenditures	General government final consumption expenditure (current US$)	NE.CON.GOVT.CD
Exports	Exports of goods and services (current US$)	NE.EXP.GNFS.CD
Foreign Reserves	Total reserves (includes gold, current US$)	FI.RES.TOTL.CD
GDP	GDP at purchaser's prices (current US$)	NY.GDP.MKTP.CD
GDPgrowth	Annual percentage growth rate of GDP at market prices based on constant local currency.	NY.GDP.MKTP.KD.ZG
Imports	Imports of goods and services (current US$)	NE.IMP.GNFS.CD
Inflation	Inflation, GDP deflator (annual %)	NY.GDP.DEFL.KD.ZG
Public external debt	External debt stocks, public and publicly guaranteed (PPG) (DOD, current US$)	DT.DOD.DPPG.CD

Source. World Bank, World Development Indicators Database, compiled by the authors.

recognized as an important factor in subsequent analyses, particularly for capturing more nuanced, time-sensitive aspects of a country's debt obligations. (Table 2 *reports definitions and sources of the utilized indicators*).

2.2. Methodology description

We presume that debt sustainability is not solely dependent on a certain threshold. Hence, public debt is influenced by public policies and the economy's resilience amidst an extremely volatile global economic climate, along with the country's ability to increase national income. Our analysis is grounded in the evolution of public external debt and economic fundamentals. We utilize both conventional methods, such as cointegration, and innovative methods, including the use of machine learning classifiers. Given that the two approaches have different specificities in terms of capturing the interactions among variables, we aim to evaluate debt position by providing a stable and reliable framework.

For the machine learning assessment, the models' inputs are as follows: the features are 'Exchange Rate', 'Expenditures', 'Exports', 'Foreign Reserves', 'GDPgrowth', 'Imports', and 'Inflation', while the target variable is 'debt sustainability'. To capture the different perceptions of public cross-border borrowing long-run viability, we redefine the condition of the target variable twice. In the first condition, debt is deemed sustainable if the growth rate of debt outstanding is less than or equal the growth rate of GDP, while in the second condition, sustainability aligns with the situation where sovereign debt evolves less than or equal to the evolution of all the macroeconomic variables, assuming that 'Inflation,' 'Expenditures', 'Debt service', and 'Imports' have negative effects on debt sustainability.

To assess whether debt is sustainable in the 22 countries, we use two machine learning classifiers, namely, the Random Forest Classifier (RFC) and Gradient Boosting Machine (GBM). The selection of these models was based on their performance. We trained multiple classifiers, retaining only the models that exhibited the best scores in terms of accuracy, precision, recall, and F1-score. The following provides insights into the key aspects of each technique.

- *Random Forest Classifier (RFC)*: is a supervised machine learning algorithm, which consists of a combination of individual decision trees, each of which is created by the ensemble learning bootstrap aggregation technique (bagging). This technique generates different training subsets from the training data, employing replacement. Based on majority voting, the final output is determined, thus improving the classification accuracy compared to a single decision tree classifier. (see Breiman, 2001; Ho, 1995)
- *Gradient Boosting Machine (GBM)* is a supervised machine-learning algorithm that belongs to ensemble methods. It provides a strong and accurate predictive model by combining multiple decision trees (i.e. weak learners). This method is based on training the weak learners on different subsets of the date, starting with a simple model, and then gradually adding new models, each of which minimizes the error of the previous model. This process of training and prediction continues until reaching the maximum number of iterations or the highest possible performance.

To deepen the study, we apply two interpretability and explanation techniques for machine learning models: Shapely Additive Explanations (SHAP) and Local interpretable model-agnostic Explanations (LIME). These techniques enhance model interpretability by providing insights into feature importance, helping to understand and classifications. SHAP values offer a unified measure of feature importance, allowing to understand each feature contribution to the model's output. LIME approximates the model locally to explain individual predictions. Understanding which features influence debt sustainability can help policy-makers in making informed decisions.

3. Results

This section presents a comprehensive presentation of findings from both econometric and machine learning assessments, revealing not only the distinctive approaches employed in handling panel data but also the disparities in accuracy and the ability to provide generalized insights. The initial subsection elucidates the outcomes of the Johansen test of cointegration, delving into the econometric perspective and unravelling patterns of long-term relationships among key variables pertinent to public external debt viability. Subsequently, the focus shifts to the machine learning subsection, where the outcomes of advanced classifiers are unveiled, demonstrating their effectiveness in discerning patterns and predicting sustainability trends. This comparative analysis not only underscores the methodological nuances between econometric and machine learning methodologies but also highlights their divergent capabilities in offering accurate and broadly applicable insights into the dynamics of public external debt sustainability.

3.1. Econometric approach

Following the approach outlined by Leachman and Francis (2000), we employed a multi-cointegration test to evaluate the sustainability of public externalities in 22 middle-income countries. We focus on examining the interplay between debt outstanding as a percentage of GDP and macroeconomic indicators. After confirming the stationarity of the variables, we conducted a Johansen cointegration test.

The results reported in Table 3 indicate the maximum rank of each country, representing the number of cointegrating vectors. The findings reveal that for all the countries examined, the rank differs from zero, providing evidence of long-term relationships among the variables. This confirmation underscores the sustainability of public external debt in 22 middle-income countries during the study period.

Given the confirmed cointegration, it is crucial to delve into the long-run influence of economic factors on public external debt position. To achieve this, we employed a Vector Error Correction Model (VECM). The results detailed in Table 4 reveal notable heterogeneity in the influence signs and statistical significance of factors across countries. This underscores the diverse set of indicators that shape the trajectory of public external debt for each country.

3.2. Machine learning approach

It is crucial to verify the performance of the two classifiers before analyzing the final classification output. From this perspective, we structure the results corresponding to each condition as follows: the evaluation metrics of both algorithms are addressed at the beginning, followed by the countries' debt situation classification. Finally, we explore the impact of the explanatory variables on debt sustainability in middle-income countries.

Condition 1: *Debt is sustainable if the growth rate of outstanding debt is less than or equal to the GDP growth rate.*

Debt sustainability depends on the country's long-run capacity to generate revenues and allocate sufficient resources towards debt servicing; thus, if debt outstanding increases faster than GDP, sustaining debt becomes more challenging. To classify middle-income countries from this perspective, we used two machine learning techniques. The preliminary tests of the two models demonstrated the robust performance of both models, with GBM slightly surpassing RFC (Table 5).

The performance of a classification model, on a specific dataset, can be evaluated by different metrics, among others we specify Precision, Recall, F1-score, and Accuracy. Table 6 summarizes the metrics for

Table 3. Cointegration test.

		Eigenvalue			
Pays	Selected Maximum Rank		Maximum	Trace statistic	Critical value 5%
Argentina	2	0.86304		93.9406	94.15
			35.0831		39.37
Azerbaijan	2	0.89506		85.0490	94.15
			43.0323		39.37
Bolivia	3	0.83079		65.5075	68.52
			30.5387		33.46
Egypt	2	0.95429		79.2163	94.15
			26.9213		39.37
Eswatini	4	0.77466		46.0009	47.21
			22.0369		27.07
Fiji	3	0.89312		45.7200	68.52
			22.5437		33.46
Ghana	2	0.89472		86.8886	94.15
			27.0098		39.37
Guatemala	4	0.76325		44.1148	47.21
			19.1038		27.07
Haiti	5	0.67861		26.4757	29.68
			17.9171		20.97
Honduras	5	0.72875		28.6987	29.68
			16.6083		20.97
Jordan	4	0.82740		40.5080	47.21
			16.6526		27.07
Mauritania	3	0.83443		61.8376	68.52
			26.4870		33.46
Morocco	2	0.90375		93.3843	94.15
			30.2327		39.37
Nepal	3	0.89273		64.9208	68.52
			24.7340		33.46
Nicaragua	3	0.84547		65.7712	68.52
			23.8096		33.46
Nigeria	5	0.68674		27.1114	29.68
			15.0625		20.97
Philippines	4	0.79767		40.9213	47.21
			24.2937		27.07
Tajikistan	2	0.91053		56.8958	94.15
			22.1742		39.37
Tanzania	3	0.94505		54.9333	68.52
			20.0048		33.46
Tunisia	4	0.79412		42.4633	47.21
			19.5080		27.07
Vanuatu	2	0.91821		86.4219	94.15
			31.6661		39.37
Vietnam	4	0.84736		40.2463	47.21
			23.4603		27.07

Source: Authors.

each class in the classification model. The results indicated that GBM generally outperformed RFC. It achieves higher precision for the 'Unsustainable' class (84% of the predicted instances by the model as unsustainable are correct), higher recall for the 'Sustainable' class (the model identifies instances as sustainable correctly, around 94% of the time), higher accuracy across both classes (the GBM F1-score is 87% for the 'Sustainable' class and 71% for the 'Unsustainable' class, while it achieves only 84% and 66% for both classes, respectively, in RFC), and a better overall predictive performance across both classes (GBM accuracy 82% vs. RFC accuracy 78%).

Table 7 reports the assessment of middle-income countries' sovereign external debt sustainability, under condition 1. The results from both models show that the debt situation in many countries was unstable during the period 2000-2021. Both classifiers confirm the sustainability of foreign borrowing, all over the period, in Guatemala, Philippines, and Tajikistan, while economies like Argentina, Azerbaijan, Eswatini, Haiti, Jordan, Morocco, Nepal, Tanzania, and Tunisia have experienced episodes of unsustainability, as shown in Figures A1 and A2. Regarding the rest of the sample, the results were not consistent between the two models in detecting the events unsustainability. Nevertheless, referring to the metrics of both algorithms, it is more suitable to prioritize GBMs classification, and therefore conclude that throughout this period, debt situation variates in Bolivia, Fiji, Ghana, Mauritania, Nicaragua, Vanuatu, and Vietnam whilst it is maintained sustainable in Egypt, Honduras, and Nigeria.

Table 4. Long-run coefficients.

	Argentina	Azerbaijan	Bolivia	Egypt	Eswatini	Fiji	Ghana
EXD_GDP	1	1	1	1	1	1	1
gdpgrowth	108.3724*	−8.75e-12	23.94222	−0.7875257**	2.505231*	4.72e + 09*	18.1969*
EXC	2.0525*	−0.2607664*	−10.66758	−0.0189692*	0.0141695	1.31e + 08*	1.071851*
Inflation	127.572*	0.1327059*	−7.073171***	−0.029915	2.424635*	7389766*	1.212717*
Exports	−1.36e-10	2.25e-12*	0.4352131*	3.42e-12**	1.65e-10**	−0.7475142*	−4.86e-10*
Expenses	2.87e-10***	1.40e-12**	−0.4805092	1.13e-11*	1.05e-10	−0.419463*	−2.39e-10*
Imports	−7.18e-10**	2.74e-12*	−0.001819	−2.46e-12**	3.51e-11	0.5191227*	3.32e-10*
Reserves	6.66e-10*	−7.64e-12*	−0.0861505	4.44e-12*	3.07e-11	0.5611174*	3.93e-11**

	Guatemala	Haiti	Honduras	Jordan	Mauritania	Morocco	Nepal
EXD_GDP	1	1	1	1	1	1	1
gdpgrowth	−0.0115997	−0.0062865	23.73534*	0.0429394	2.658593*	0.09566	0.4786089*
EXC	−0.0819494*	−0.0021233*	−0.246412*	0.0159026	−0.0533728*	−0.0874995*	−0.0060941*
Inflation	0.449202*	−0.0140401	0.1175742	−1.933817	6.54e-10*	−0.0606956	0.005423
Exports	1.24e-11*	−1.67e-10*	−1.79e-10*	3.46e-10**	3.17e-12	2.73e-11*	1.65e-11**
Expenses	1.49e-12	−1.20e-11	8.30e-10*	−5.22e-10	1.69e-09*	1.32e-13	1.27e-10*
Imports	−8.72e-12*	3.80e-11	−1.98e-11	−5.51e-11	−5.48e-11*	−2.04e-11*	−1.76e-11*
Reserves	2.65e-12*	8.49e-11*	5.03e-10*	1.06e-11	5.59e-11	−1.48e-12	4.10e-11*

	Nicaragua	Nigeria	Philippines	Tajikistan
EXD_GDP	1	1	1	1
gdpgrowth	−3.50296	1.219886*	1.403957	−1.25e-09*
EXC	0.1796639*	−0.000326*	−0.0085059*	0.0892328*
Inflation	−0.2133148	−0.44749*	9.16e-09*	0.0387037*
Exports	−4.33e-10	−1.78e-17*	−1.59e-17*	4.46e-10*
Expenses	8.47e-10	5.15e-12*	2.68e-11*	1.04e-09*
Imports	6.67e-10*	6.92e-12*	−5.05e-16	−1.41e-10*
Reserves	−1.80e-09*	1.09e-12*	−3.16e-12**	−7.34e-10*

	Tanzania	Tunisia	Vanuatu	Vietnam
EXD_GDP	1	1	1	1
gdpgrowth	221.7512*	−2.042022	−1.36e-09*	−7.449251*
EXC	−0.008821**	−0.0601966	−0.00678*	−0.000762*
Inflation	−3.811647	−8.525594*	1.09e-09*	0.9925816*
Exports	7.39e-09*	−5.04e-11	−4.06e-10*	−3.70e-12*
Expenses	5.78e-09*	−9.72e-11**	−5.09e-10*	1.21e-11*
Imports	−2.95e-09**	5.23e-11	2.50e-10*	9.87e-12*
Reserves	−1.02e-08*	5.87e-11**	−3.78e-10*	−1.36e-11*

Note. *, **, and, *** denote significance at the 1%,5% and 10% levels, respectively. Source: Authors.

Table 5. First condition's Cross Validation.

Random Forest Classifier	Accuracy scores	**[0.95 0.945 0.915 0.95 0.94]**
	Mean accuracy	0.939998
Gradient Boosting Machine	**Accuracy scores**	**[0.96 0.95 0.92 0.95 0.96]**
	Mean accuracy	0.94801

Source: Authors.
The bold values represent the highest accuracy scores achieved by the model across multiple evaluations. Consistently high performance with scores above 91%, underscores the model's reliability and generalizability, indicating robustness across different data splits.

Table 6. First condition's performance metrics.

		Precision	Recall	F1-score	Support
Random Forest Classifier	Sustainable	0.84	0.85	0.84	66
	Unsustainable	0.67	0.65	0.66	31
	Accuracy			**0.78**	97
	Macro avg	0.75	0.75	0.75	97
	Weighted avg	0.78	0.78	0.78	97
Gradient Boosting Machine	Sustainable	0.82	0.94	0.87	63
	Unsustainable	0.84	0.62	0.71	34
	Accuracy			**0.82**	97
	Macro avg	0.83	0.78	0.79	97
	Weighted avg	0.83	0.82	0.82	97

Source: Authors.
The bold values highlight overall predictive performance, demonstrating again the superior performance of GBM over RFC.

To understand the model classification, we utilize the SHAP technique, which can provide insights into what the algorithm learns from the given data. Figure 1 corresponding to RFC SHAP, reports that all the features have the same degree of influence on both classes, and GDP growth is the most

Table 7. First condition's classification outcome.

	Random Forest Classifier		Gradient Boosting Machine	
Country	Sustainable	Unsustainable	Sustainable	Unsustainable
Argentina	✓	✓	✓	✓
Azerbaijan	✓	✓	✓	✓
Bolivia	✓		✓	✓
Egypt	✓	✓	✓	
Eswatini	✓	✓	✓	✓
Fiji	✓		✓	✓
Ghana	✓		✓	✓
Guatemala	✓		✓	
Haiti	✓	✓	✓	✓
Honduras	✓	✓	✓	
Jordan	✓	✓	✓	✓
Mauritania	✓		✓	✓
Morocco	✓	✓	✓	✓
Nepal	✓	✓	✓	✓
Nicaragua	✓		✓	✓
Nigeria	✓	✓	✓	
Philippines	✓		✓	
Tajikistan	✓		✓	
Tanzania	✓	✓	✓	✓
Tunisia	✓	✓	✓	✓
Vanuatu	✓		✓	✓
Vietnam	✓		✓	✓

Source: Authors.

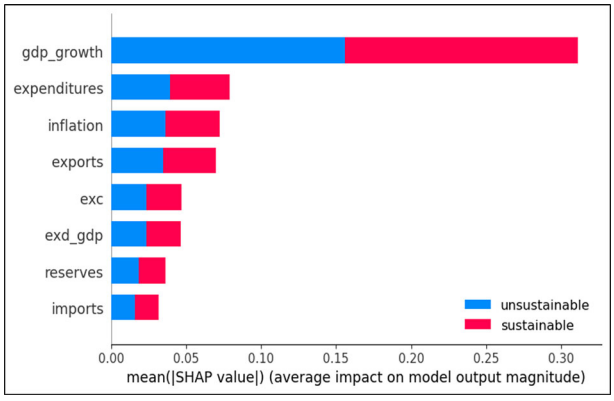

Figure 1. RFC- SHAP.
Source: Authors.

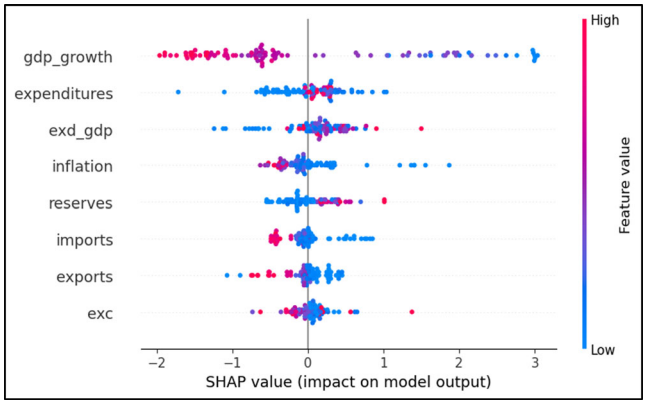

Figure 2. GBM- SHAP.
Source: Authors.

determinant feature impacting debt situation classifications, followed by expenditures, inflation, exports, exchange rate, level of indebtedness, foreign reserves, and imports. The SHAP output for the GBM (Figure 2) reveals that the debt position is influenced by GDP growth, inflation, imports, and exports.

Notably, the impact of these features weakened as their respective attribute values increased. By contrast, the contribution of the level of indebtedness and foreign reserves to debt sustainability classification increases with an increase in SHAP attribution. Regarding public expenditure and exchange rates, their effects become important only when the features are associated with specific values.

LIME results presented in Figures 3 and 4 indicate that GBM is more confident to predict the unsustainability of public external debt with a probability of 92% compared to RFC which assigns only 58% for this class, and the prediction confidence results reverse in the case of the 'Sustainable' class. Both models demonstrate that the exchange rate contributes towards sustainability, but its importance is still weak, as it does not exceed 2%. Regarding other features, the models report different influences of each variable on the debt situation, and these results can be justified by the studied value fixed by each model. For example, within a 2% level of inflation, RFC classifies debt as sustainable, while within a 14% level, GBM considers that debt is unsustainable, and both results are logical because controlled inflation helps maintain sustainable debt, while high inflation can lead to debt distress events. Overall, the combined results of the two models provide insights into the patterns of the relationship between debt sustainability and the macroeconomic variables. First, the dependence follows a non-linear pattern. A specific threshold exists for each key macroeconomic variable that determines the sustainability of external public debt. Second, the relationship between debt long-run viability and economic growth is non-linear and influenced by other factors. Third, the macro-financial literature has largely studied the maximum limit beyond which debt struggles with economic growth and might be perceived as unsustainable, disregarding the minimum level; the present results demonstrate that there exists an optimal interval of debt where sustainability is satisfied. Fourth, accumulating high levels of foreign reserves enhances debt sustainability (this finding is in line with Amstad et al., 2020; Sabbadini, 2019; Corneli & Tarantino, 2016). Fifth, a substantial disproportion between imports and exports and high government expenditures strains debt sustainability.

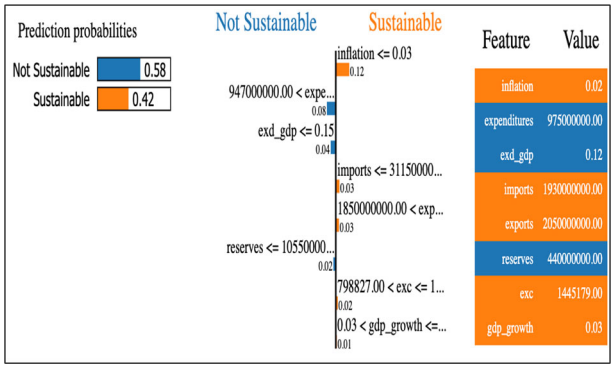

Figure 3. RFC- LIME.
Source: Authors.

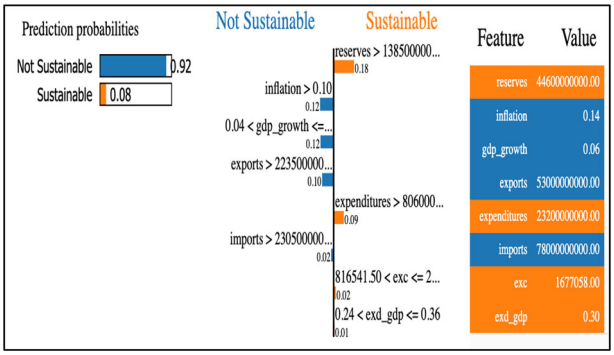

Figure 4. GBM- LIME.
Source: Authors.

Condition 2: *Debt is sustainable if the growth rate of debt outstanding is less than or equal the evolution of all the macroeconomic variables, assuming that 'Inflation', 'Expenditures', 'Debt service' and 'Imports' have negative effects on debt sustainability.*

Recognizing that analyzing debt sustainability considering only the first condition can be perceived as a limited study, since Condition 1 oversimplifies the complexity of foreign borrowing assessment by considering only the nexus between the growth rates of debt outstanding and GDP. So, in order to improve the study, we reconduct the first models by including other variables as to capture the interaction between macroeconomic fundamentals and debt sustainability, assuming that 'Inflation', 'Expenditures', 'Debt service', and 'Imports' have negative effects on debt sustainability. The evaluation metrics of the models are presented in Tables 8 and 9. The results confirmed the strong performance of the models, with a slightly better prediction observed in GBM, with an excellent overall prediction accuracy across both models. Based on the classification report metrics, GBM surpassed RFC within both classes in terms of definition, prediction, and accuracy.

The results presented in Table 10, as well as in Figures B1 and B2, indicate that incorporating supplementary indicators significantly improved classification accuracy. Specifically, the accuracy for RFC increased from 78% to 91%, and for GBM from 82% to 95% (Table 9). Initially, the outcomes varied between 'sustainable' and 'experiencing episodes of unsustainability,' without confirming any cases of unsustainability among the studied countries. However, under the second condition, debt unsustainability was confirmed by both classifiers for Haiti, and by GBM alone for Argentina, Ghana, and Tajikistan. Given that we prioritize results from higher performing algorithm in cases of divergent classifications, we identify four countries with unsustainable debt over the period 2000-2021. For the rest of the sample, both classifiers state that the public external has experienced some episodes of unsustainability, which is almost consistent with the classification under the first condition.

Based on the SHAP graph (Figure 5), it is observed that all the variables exert a similar level of influence on the prediction of 'Sustainable' and 'Unsustainable' classes. Inflation emerged as the most influential feature, closely followed by exports, GDP growth, reserves, debt service, and expenditures with a notable gap between their respective contributions. The seventh feature driving the model's outcomes is debt outstanding succeeded by exchange rate and imports.

In the context of GBM classification, SHAP values indicate that 'Inflation' and 'Expenditures have substantial impacts on a country's long-term debt viability, with their effects strengthening as their respective attribute values increase. This pattern is similar for imports and debt service. Conversely, the effects of foreign reserves, exports, and GDP growth effects weaken as the SHAP attribute of each indicator increases. The effect of level of indebtedness follows a U-shaped pattern (Figure 6).

Table 8. Second condition's Cross Validation.

Random Forest Classifier	Accuracy scores	**[0.93 0.925 0.94 0.955 0.95]**
	Mean accuracy	0.940
Gradient Boosting Machine	**Accuracy scores**	**[0.935 0.935 0.955 0.965 0.95]**
	Mean accuracy	0.948

Source: Authors.
The bold values represent the highest accuracy scores achieved by the model across multiple evaluations. Consistently high performance with scores above 91%, underscores the model's reliability and generalizability, indicating robustness across different data splits.

Table 9. Second condition's performance metrics.

		Precision	Recall	F1-score	Support
Random Forest Classifier	Sustainable	0.90	0.91	0.91	103
	Unsustainable	0.91	0.90	0.90	97
	Accuracy			**0.91**	200
	Macro avg	0.91	0.90	0.90	200
	Weighted avg	0.91	0.91	0.90	200
Gradient Boosting Machine	Sustainable	0.91	0.98	0.94	137
	Unsustainable	0.98	0.92	0.95	163
	Accuracy			**0.95**	300
	Macro avg	0.95	0.95	0.95	300
	Weighted avg	0.95	0.95	0.95	300

Source: Authors.

Table 10. Second condition's classification outcome.

	Random Forest Classifier		Gradient Boosting Machine	
Country	Sustainable	Unsustainable	Sustainable	Unsustainable
Argentina	✓	✓		✓
Azerbaijan	✓	✓	✓	✓
Bolivia	✓	✓	✓	✓
Egypt	✓	✓	✓	✓
Eswatini	✓	✓	✓	✓
Fiji	✓	✓	✓	✓
Ghana	✓	✓		✓
Guatemala	✓		✓	✓
Haiti		✓		✓
Honduras	✓	✓	✓	✓
Jordan	✓	✓	✓	✓
Mauritania	✓	✓	✓	✓
Morocco	✓	✓	✓	✓
Nepal	✓	✓	✓	✓
Nicaragua	✓	✓	✓	✓
Nigeria	✓	✓	✓	✓
Philippines	✓	✓	✓	✓
Tajikistan	✓	✓		✓
Tanzania	✓	✓	✓	✓
Tunisia	✓	✓	✓	✓
Vanuatu	✓	✓	✓	✓
Vietnam	✓	✓	✓	✓

Source: Authors.

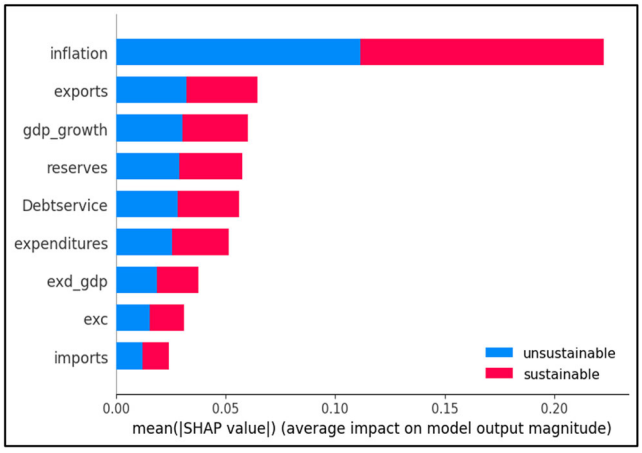

Figure 5. RFC- SHAP.
Source: Authors.

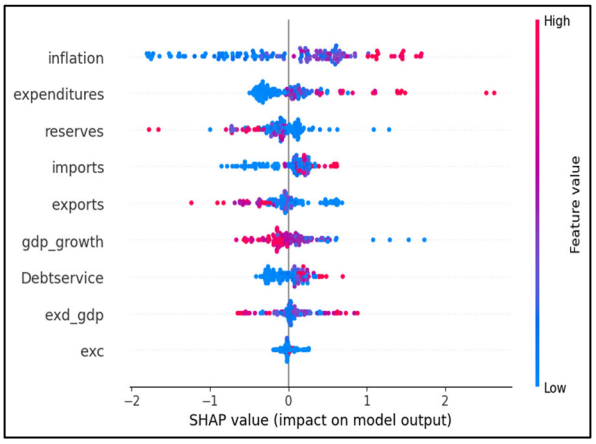

Figure 6. GBM- SHAP.
Source: Authors.

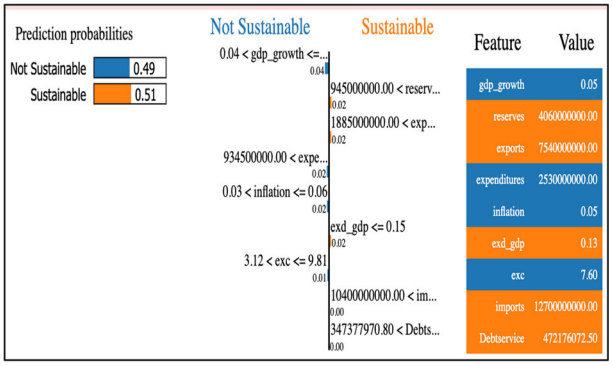

Figure 7. RFC- LIME.

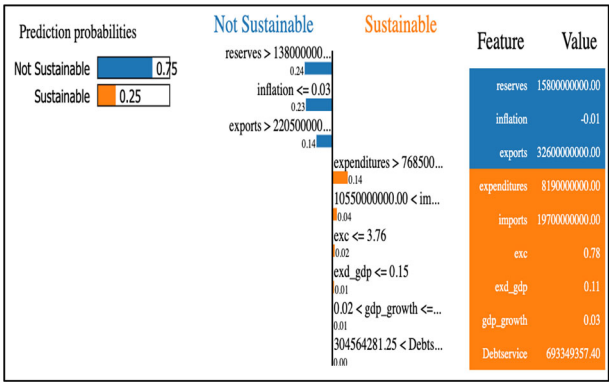

Figure 8. GBM- LIME.

LIME results (Figures 7 and 8) indicate that 'Sustainable' class is better predicted by RFC model, with a prediction probability of 51%, compared to 25% using GBM. Conversely, the likelihood of predicting the 'Unsustainable' class is greater with GBM, reaching 75% versus 49% with the RFC model. LIME tests for both classifiers show that the accumulation of foreign reserves and external debt contributes to the sustainability of foreign borrowing, as long as they do not exceed certain levels, beyond these thresholds, the effect reverses. The results also demonstrate that slower GDP growth and moderate exports, which could be interpreted as signs of a country's economic stability, positively affect maintaining sustainable foreign debt. This is because the government can better manage its debt, allocating sufficient resources toward debt servicing. A depreciation of exchange rate is found to be a factor of the unsustainability of debt in developing countries, highlighting the importance of the sound monetary policy and exchange rate regimes in stabilizing the domestic currency to strengthen the countries' external debt position. The effect of debt service on sovereign foreign borrowing sustainability is inconsequential. Higher imports and Expenditures have a positive influence on debt long-run viability, indicating that these indicators stimulate economic activity, consequently improving the capacity to repay. In both classifications, low Inflation or Inflation higher than the common target (2%) contributes to the unsustainability of external borrowing, with a more significant effect when inflation is negative. This demonstrates the necessity of maintaining inflation at an adequate level.

4. Discussion

The findings of this study provide notable insights into the assessment of public foreign borrowing and factors influencing debt sustainability in middle-income countries. Using econometric methods, debt sustainability is evaluated individually rather than collectively in a panel, revealing diverse influences of macroeconomic fundamentals on debt positions across countries. This variability complicates the generalization of factors impacting debt sustainability across different nations.

The application of machine learning techniques introduces concerns regarding reliable and correct interpretations, requiring a cautious approach. The classification outcomes demonstrate that altering the macroeconomic conditions in each iteration results in a reclassification of countries' debt positions. This highlights the sensitivity of debt long-term viability to fluctuations in these fundamentals. Consequently, the study emphasizes that debt sustainability is not determined solely by the level of indebtedness; rather, it is contingent on public policies, economic resilience amid an extremely volatile global economic climate, and a country's capacity to boost national income.

The utilization of Shapely additive explanations (SHAP) and local interpretable model-agnostic explanations (LIME) uncovers interesting aspects on how each feature studied affects debt sustainability. The overall results demonstrate that managed inflation and slow GDP growth represent the most important indicators promoting foreign borrowing sustainability in middle-income countries. These findings underscore the importance of maintaining comprehensive stability to ensure long-run viability of sovereign external debt. Specifically, low inflation rate and steady GDP growth allow public authorities to stabilize national income, currency values, and foreign borrowing costs.

The accumulation of foreign reserves also plays a significant role in debt sustainability, as international reserves can mitigate the risks of default and currency depreciation, enhancing the creditworthiness of sovereign debt denominated in foreign currency. However, our results show that beyond a certain threshold, excessive reserves may weaken debt sustainability. Government spending also contribute to sustainable debt if it remains within reasonable limits and is efficiently allocated. Additionally, exports play a dual role: while they enhance economic performance and facilitate debt commitments, mismanagement of external trade can negatively affect sovereign external debt sustainability.

Despite efforts by monetary authorities to manage exchange rate fluctuations, our findings suggest that exchange rates remain a key determinant of debt unsustainability. This raises concerns about the soundness of monetary policy and debt management strategy, particularly regarding the composition of external debt currency composition and the management of currency mismatches.

Regarding debt servicing, the two machine learning explanation techniques present divergent interpretations. SHAP outputs suggest that debt servicing significantly influences debt positions globally, indicating that countries with high debt service obligations may face greater challenges in maintaining sustainable debt levels. In contrast, LIME results show that the impact of debt servicing is unsubstantial in local contexts, reflecting country-specific conditions. This is particularly relevant for middle-income countries, which often benefit from concessional loans.

The limited impact of debt servicing in our LIME analysis may also be attributed to short-term fiscal strategies that alleviate debt servicing pressures, as well as access to international financial markets, which may buffer the immediate impact of debt servicing on overall debt sustainability. While these results highlight the substantial role of strategies and policies in preserving sovereign external debt position, they also reveal a limitation in our analysis: the exclusion of the interest rate responses to debt. Although this decision was made to maintain a focus on macroeconomic fundamentals and policy actions, it is important to acknowledge that interest rates play a critical role in debt dynamics. Future research should incorporate this factor for more comprehensive assessment of debt sustainability. Furthermore, access to more granular data could improve the accuracy of our model's predictions and extend its applicability to different income groups.

5. Conclusion

The econometric approaches used to assess debt sustainability have many limitations in apprehending complex relationships between the variables and providing a detailed analysis of countries' debt situations throughout the analyzed period. We propose to evaluate debt position using machine learning techniques, since they can achieve higher accuracy and precision than econometric models (as proven in many studies), offer deeper insights into different debt situations of each country, and capture the different patterns followed by the variables. To the best of our knowledge, this study is the first to propose an analysis of middle-income countries' debt sustainability using Artificial intelligence methods. We applied both the Random Forest Classifier and Gradient Boosting Machine to determine the cross-border

borrowing positions corresponding to each country from the 22 countries constituting our sample, and during the period 2000-2021. The SHAP and LIME techniques were used to estimate the contribution of each feature to the model outcomes.

The machine learning results offer valuable assessments of a country's debt trajectory, distinguishing between sustainability, unsustainability, or episodes of unsustainability. This contrasts with conventional econometric models that evaluate debt sustainability based on overall period tendencies. The use of machine learning techniques reveals significant insights. First, the position of public foreign debt depends on the soundness of macroeconomic policy. Second, the interactions between debt sustainability and macroeconomic fundamentals follow a non-linear pattern. Third, in the case of middle-income countries, debt distress episodes are caused mainly by inflation, foreign reserves, and external trade imbalances but not by the level of indebtedness or its service, reflecting that debt long-run viability is more influenced by the coherence between debt management strategy and public economic policies than debt outstanding. Regarding other indicators, their respective effects were conditioned by their levels. In this study, we attempted to extend sovereign cross-border borrowing sustainability assessments by including the interactions between the debt situation and macroeconomic indicators; however, debt sustainability is more complex and influenced by institutional and governance factors and social and environmental factors besides external conditions, which can be examined in further research.

Authors' contribution

Fatima-Ezzahra RAFIE and Mostafa LEKHAL were both involved in the conception and design, the analysis and interpretation of the data, as well as in the drafting and critical revision of this work. Both authors have contributed equally to this research project.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability Statement

The data utilized in this research paper, sourced from the World development Indicators database provided by the World Bank, is available upon request. Additionally, the Python code script used to implement the machine learning algorithms described in this study is also available upon request. Interested parties may contact the corresponding author for access to the data and code script. We are committed to promoting transparency and reproducibility in our research, and we encourage further exploration and validation of our findings by providing access to both the data and code.

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