STATISTICS, OPTIMIZATION AND INFORMATION COMPUTING
Stat., Optim. Inf. Comput., Vol. **16**, July 2026, pp 389–402.

A Tokenized Sovereign Debt Conversion Mechanism for Dynamic Public Debt Reduction

Kiarash Firouzi*

Department of Mathematics, Allameh Tabataba'i University, Iran

Abstract This paper proposes the Tokenized Sovereign Debt Conversion Mechanism (TSDCM), a decentralized finance (DeFi) instrument designed to automate sovereign debt reduction through smart-contracted triggers. By integrating a two-state regime-switching jump-diffusion framework, the TSDCM converts traditional bonds into performance-linked tokens when predefined debt-to-GDP and growth thresholds are met. We provide rigorous theoretical proofs for finite-time activation and pathwise debt dominance, addressing the "holdout problem" via integration with Collective Action Clauses (CACs). Calibrated using IMF data from 30 emerging markets (2000–2022) and verified through sensitivity analysis including post-2022 shocks, Monte Carlo simulations report a 20–25% reduction in expected debt ratios and over 60% lower default probabilities. By solving the "Oracle Problem" through a multi-source decentralized data network and aligning creditor-debtor incentives via growth-participation tranches, the TSDCM offers a robust, legally enforceable, and technologically transparent blueprint for sustainable sovereign debt management.

Keywords Sovereign debt, Tokenization, Jump-diffusion, Regime-switching, Smart contracts, Debt conversion, Decentralized finance, Policy innovation

AMS 2010 subject classifications 91G80, 60H10, 60J75, 60J27, 91B28

DOI: 10.19139/soic-2310-5070-3108

1. Introduction

Globally, the volume of sovereign debt has increased, limiting fiscal policy options and increasing default risk, especially in developing nations. Conventional debt-relief strategies, such as Collective Action Clauses, IMF standby agreements, or Paris Club negotiations, are frequently slow, politicized, and not very flexible when faced with sudden macroeconomic changes. These constraints drive the creation of transparent, flexible tools that can pay off debt in accordance with the state of the economy [19].

When debt and growth conditions are satisfied, we suggest the Tokenized Sovereign Debt Conversion Mechanism (TSDCM), which uses blockchain-enabled smart contracts to convert a portion of outstanding bonds. TSDCM aligns the incentives of creditors and debtors: creditors receive exposure to future upside through tokens that can be redeemed based on macroeconomic outcomes, while governments receive automatic relief upon attaining improvements in fiscal health.

Although corporate debt and project finance have been the main focus of existing performance-linked instruments, sovereign applications have not received enough attention. In addition to automating debt relief, TSDCM makes it possible to instantly match the goals of macroeconomic policy with the returns of creditors [29, 23]. TSDCM addresses the liquidity premium traditionally associated with state-contingent debt by providing a standardized, programmable format that facilitates secondary-market trading through automated market-making protocols. Our contributions are four-fold:

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*Correspondence to: Kiarash Firouzi (Email: k_firouzi@atu.ac.ir). Department of Mathematics, Allameh Tabataba'i University. Dehkadeh Olympic, Tehran, Iran

ISSN 2310-5070 (online) ISSN 2311-004X (print)

- Creation of sovereign debt dynamics through jump-diffusion processes that switch regimes.
- Stochastic hitting-time triggers associated with debt-to-GDP and GDP growth thresholds are defined and analyzed.
- Finite-time activation and guaranteed expected debt reduction are demonstrated, leading to a new main theorem.
- MATLAB Monte Carlo simulations and IMF and World Bank data were used to calibrate the impact of TSDCM.

The remainder of this paper is organized as follows:

Relevant literature on DeFi applications, stochastic modeling, and sovereign debt restructuring is reviewed in Section 2. The mathematical framework is developed in Section 3, which also defines the debt-conversion triggers and the regime-switching jump-diffusion dynamics. The primary theoretical findings—finite-time activation, pathwise debt ordering, and expected debt reduction—are also presented in Section 3, which also concludes with the guaranteed positive reduction theorem. Key empirical findings are reported in Section 4, which also explains the calibration and Monte Carlo simulation methodology. Policy implications and implementation considerations are covered in Section 5. Section 6 wraps up and identifies directions for further study.

2. Literature Review

The mechanisms and results of debt renegotiations are the focus of the empirical and institutional branches of sovereign debt research. A thorough analysis of restructuring episodes since the 1970s is given by Das, Papaioannou, and Trebesch [13], who categorize preemptive, weakly preemptive, and post-default operations. While Asonuma, Erce, and Sasahara [4] compile stylized facts on negotiation delays, haircut magnitudes, and jurisdictional enforcement, Tomz and Wright [28] document how creditor strategies around holdouts and litigation evolve endogenously. Collective Action Clauses (CACs) significantly lower holdout litigation costs, according to Cruces and Trebesch [12]. However, enforcement heterogeneity across governing laws (e.g., New York vs. English law) still results in a wide range of creditor recoveries. While Collective Action Clauses (CACs) play a critical role in sovereign debt restructuring by mitigating coordination failures among creditors post-default, they do not constitute ex-ante debt relief mechanisms. In contrast, instruments such as Contingent Convertible Bonds (CoCos) and GDP-linked bonds offer genuine risk-sharing features by adjusting debt service obligations in response to macroeconomic triggers ([10, 11]). This paper focuses on integrating such countercyclical instruments into a tokenized framework, rather than relying on contractual restructuring clauses like CACs.

From a theoretical perspective, Eaton and Gersovitz's groundbreaking model [14] presents sovereign default as a recursive-contract issue with endogenous penalties. Arellano [3] calibrates a long-term debt environment to Latin American data, while Aguiar and Gopinath [1] expand this to emerging-market U-shaped consumption profiles. More recent research incorporates stochastic volatility under incomplete markets [24], adds Poisson-driven jumps to reflect abrupt financing freezes [30], and embeds regime-switching dynamics into sovereign risk models to capture shifts between peaceful and crisis states [2, 20]. These extensions show that when growth rates or spreads cross critical values, threshold-based debt-relief triggers can arise naturally.

In addition to these threads, research on state-contingent or performance-linked debt instruments explores ways to distribute macroeconomic risk. While Broner et al. [5] and Sturzenegger and Zettelmeyer [27] examine menu auctions for sovereigns to select among contingent payoff structures, Eichengreen and Mody [15] support GDP-indexed bonds to match debt service with growth realizations. Despite the fact that these studies demonstrate the benefits of risk sharing, large-scale issuance has been hindered by practical issues such as creditor heterogeneity, market liquidity, and data verifiability.

Programmable debt protocols that automate conditional conversions have been sparked by the emergence of decentralized finance (DeFi). Cisar et al. [8] outline a vision for tokenized sovereign bonds, while Christidis and Devetsikiotis [7] demonstrate how blockchain oracles can safely feed macro data on-chain. More recent prototypes by Lee and Park [18] offer preliminary evidence of trigger-based reductions, while Moin et al. [21] use automated triggers and multi-signature governance to amortize debt under predetermined conditions. However, formal activation guarantees and a unified stochastic foundation are frequently absent from these architectures. This is addressed by the Tokenized Sovereign Debt Conversion Mechanism (TSDCM), which provides analytical proofs of finite-time activation and expected debt reduction by integrating a calibrated regime-switching jump-diffusion framework into smart contracts.

3. Mathematical Framework

The tokenized conversion mechanism suggested in this paper is based on a stochastic model for the evolution of sovereign debt that is laid out in this section. We identify the exact circumstances in which sovereign debt automatically transforms into tokenized instruments and use regime-switching jump-diffusion processes to capture macroeconomic uncertainty. By associating conversion events with measurable gains in national debt ratios and growth performance, this mechanism strengthens fiscal restraint.

3.1. Stochastic Sovereign Dynamics

Let $(\Omega, \mathcal{F}, \{\mathcal{F}_t\}, \mathbb{P})$ be a filtered probability space supporting the following components:

1. Standard Brownian motions W_t and W_t', possibly correlated.
2. Poisson processes N_t and M_t modeling sudden economic or fiscal events.

We define:

1. D_t: Sovereign debt-to-GDP ratio at time t.
2. g_t: Instantaneous GDP growth rate.
3. $R_t \in \{0,1\}$: Macroeconomic regime indicator, where 0 denotes expansion and 1 denotes crisis.

Regime transitions follow a continuous-time Markov process with generator matrix Q:

$$Q = \begin{pmatrix} -\lambda_{01} & \lambda_{01} \\ \lambda_{10} & -\lambda_{10} \end{pmatrix},$$

where λ_{ij} is the rate of switching from regime i to regime j.

Debt Ratio Dynamics In regime $r \in \{0,1\}$, the debt ratio D_t evolves as:

$$dD_t = (a_r - b_r D_t)\, dt + \sigma_r D_t \, dW_t + J_r D_{t^-} \, dN_t, \tag{3.1}$$

with parameters:

1. a_r: Base fiscal expansion rate.
2. b_r: Debt sustainability pressure.
3. σ_r: Volatility in debt accumulation.
4. $J_r \sim \text{LogNormal}(\mu_r^J, \sigma_r^J)$: Shock amplitude for jump events.
5. κ_r: Intensity of Poisson process N_t in regime r.

GDP Growth Dynamics Likewise, GDP growth g_t follows:

$$dg_t = (c_r - d_r g_t)\, dt + \eta_r g_t \, dW_t' + K_r g_{t^-} \, dM_t, \tag{3.2}$$

with c_r, d_r, η_r governing drift and volatility; and $K_r \sim \text{LogNormal}(\mu_r^K, \sigma_r^K)$ modeling growth shocks.

3.2. Trigger-Based Debt Conversion

The tokenization mechanism operates via smart contracts embedded in sovereign debt tokens. These contracts monitor macroeconomic indicators and activate relief measures when predefined thresholds are breached. Specifically, debt relief is triggered when the debt-to-GDP ratio exceeds D^* and GDP growth falls below $g\star$, ensuring countercyclical support. This design aligns with the principles of risk-sharing and macroeconomic stabilization.

Our tokenized mechanism activates when the sovereign meets both:
-Debt ratio improvement: $D_t \leq D^*$ for some threshold D^*, and
-Growth rebound: $g_t \geq g^*$ for a threshold g^*.

Let the respective first hitting times be:

$$\tau_D = \inf\{t \geq 0 \mid D_t \leq D^*\}, \quad \tau_g = \inf\{t \geq 0 \mid g_t \geq g^*\}.$$

Define the activation time as:

$$\tau = \max(\tau_D, \tau_g).$$

At τ, the smart contract executes together with:

1. Debt Reduction: A fraction $\alpha \in (0,1)$ of D_t is retired:

$$D_\tau = (1-\alpha) D_{\tau^-}.$$

2. Token Issuance: Creditors receive tokens redeemable at future date T as:

$$\text{Payout} = \beta \max(D_\tau - D^*, 0) + \gamma \int_\tau^T (g_s - g^*)^+ \, ds,$$

   where β, γ tune the sensitivity to excess debt and above-target growth.

Both D_t and g_t evolve from (D_τ, g_τ) under the same dynamics after conversion.

Proposition 3.1. *(Finite-Time Trigger Activation) Let the sovereign economy enter a regime r such that:*

$$a_r - b_r D^* > 0, \quad \textit{and} \quad c_r - d_r g^* > 0.$$

Then the trigger time $\tau = \max(\tau_D, \tau_g)$, defined as the first time both $D_t \leq D^*$ and $g_t \geq g^*$, occur almost surely in finite time. That is,

$$\mathbb{P}(\tau < \infty) = 1.$$

Proof We analyze the debt ratio D_t and the growth process g_t separately under regime r.
-Debt Dynamics: Consider the SDE

$$dD_t = (a_r - b_r D_t)\, dt + \sigma_r D_t \, dW_t + J_r D_{t^-} \, dN_t,$$

The drift term $(a_r - b_r D_t)$ is strictly positive when $D_t < \frac{a_r}{b_r}$ and strictly negative when $D_t > \frac{a_r}{b_r}$. Assume $D^* < \frac{a_r}{b_r}$, then D_t has a negative drift above D^*, pulling it downward.

Meanwhile, the jump term $J_r D_{t^-} dN_t$ ensures additional downward movement due to negative fiscal shocks with nonzero probability (since J_r can be negative with positive probability under LogNormal support with $\mu_r^J < 0$). Because Poisson processes have intensity $\kappa_r > 0$, they introduce discrete movements at random intervals.

Let us define a Lyapunov function $V(D_t) = (D_t - D^*)^2$. Then:

$$\mathcal{L}V(D_t) = \frac{d}{dt}\mathbb{E}[V(D_t)] = 2(D_t - D^*)(a_r - b_r D_t) + \sigma_r^2 D_t^2.$$

Above D^*, this generator is strictly negative under our parameter assumptions, reinforcing mean reversion toward D^*.

-Growth Dynamics: Analogously, consider

$$dg_t = (c_r - d_r g_t)\,dt + \eta_r g_t\,dW'_t + K_r g_{t^-}\,dM_t.$$

Suppose $g^* < \frac{c_r}{d_r}$, then g_t has positive drift below g^* and is pushed upward. With M_t carrying nonzero jump intensity ξ_r, occasional positive growth shocks contribute to upward movement.

Using standard results from stochastic calculus (see [25]), the expected hitting time of a level by a jump-diffusion with drift aligned toward the threshold is finite.

Since both D_t and g_t are ergodic under these assumptions and have non-zero variance and jump probability [16, 22], their respective hitting times τ_D and τ_g are finite almost surely. Therefore,

$$\mathbb{P}(\tau = \max(\tau_D, \tau_g) < \infty) = 1.$$

□

Proposition 3.2. *(Pathwise Dominance After Conversion) Let D_t^C and D_t^0 represent the debt ratio with and without conversion, respectively. Suppose the drift $\mu(D) = a_r - b_r D$ is decreasing in D and the volatility $\sigma_r D$ is increasing in D. Then:*

$$D_t^C \le D_t^0, \quad \textit{for all } t \ge \tau \quad \textit{almost surely}.$$

Proof At time τ, the conversion reduces the debt:

$$D_\tau^C = (1-\alpha) D_{\tau^-}^0,$$

and immediately initializes a process with a strictly lower starting point.

Let us analyze the SDEs for each case:
-Baseline: $dD_t^0 = \mu(D_t^0)\,dt + \sigma_r D_t^0\,dW_t + J D_{t^-}^0\,dN_t$
-Converted: $dD_t^C = \mu(D_t^C)\,dt + \sigma_r D_t^C\,dW_t + J D_{t^-}^C\,dN_t$
Since $\mu(D)$ is decreasing, we have:

$$\mu(D_t^C) \ge \mu(D_t^0), \quad \text{and} \quad \sigma_r D_t^C \le \sigma_r D_t^0.$$

Assume that both processes share the same Brownian motion and jump processes. Apply the Comparison Theorem for Jump-Diffusions (see [6]): if two SDEs satisfy the same noise sources and one has a lower initial condition and higher drift (and lower volatility), then the path remains below the other almost surely. Therefore, for all $t \ge \tau$:

$$D_t^C \le D_t^0, \quad \text{a.s.}$$

□

Proposition 3.3. *(Expected Debt Reduction at Maturity) Let T be the terminal date of the token maturity. Then:*

$$\mathbb{E}[D_T^C] \le \mathbb{E}[D_T^0] - \alpha D^* \cdot \mathbb{P}(\tau \le T).$$

Proof Define indicator function $\mathbf{1}_{\{\tau \le T\}}$ and apply the law of total expectation:

$$\mathbb{E}[D_T^C] = \mathbb{E}[D_T^C \cdot \mathbf{1}_{\{\tau \le T\}}] + \mathbb{E}[D_T^C \cdot \mathbf{1}_{\{\tau > T\}}].$$

On $\{\tau > T\}$, no conversion occurs and $D_T^C = D_T^0$.

On $\{\tau \le T\}$, the debt is reduced by at least αD^* and path remains below D_t^0 by Proposition 3.2. Assume that average post-conversion drift remains negative (due to low D_τ), yielding further reduction relative to baseline.

Thus:

$$\mathbb{E}[D_T^C] = \mathbb{E}[D_T^0] - \mathbb{E}[\Delta_t \cdot \mathbf{1}_{\{\tau \le T\}}] \le \mathbb{E}[D_T^0] - \alpha D^* \cdot \mathbb{P}(\tau \le T).$$

Where Δ_t is the reduction due to conversion and downward path divergence.

This proves that the mechanism delivers expected debt relief proportional to the probability of activation and the policy-defined reduction magnitude αD^*. □

3.3. *Main Theorem: Expected Net Fiscal Improvement under TSDCM*

Theorem 3.4. *Consider a sovereign governed by regime-dependent debt and growth dynamics as previously defined. Let the tokenized debt conversion mechanism activate at time τ when:*

$$D_t \le D^*, \quad g_t \ge g^*,$$

for thresholds $D^* > 0$ and $g^* > 0$. Suppose:

1. *In regime r, the drift conditions $a_r - b_r D^* > 0$ and $c_r - d_r g^* > 0$ hold.*
2. *The mechanism reduces debt by fraction $\alpha \in (0, 1)$ at τ.*
3. *Token payout at maturity T is:*

$$\Pi_T = \beta \max(D_\tau - D^*, 0) + \gamma \int_\tau^T (g_s - g^*)^+ ds,$$

Then, the mechanism delivers an "expected net fiscal benefit" defined by:

$$\mathbb{E}[D_T^0 - D_T^C - \Pi_T] \ge \alpha D^* \cdot \mathbb{P}(\tau \le T) - \beta \cdot \mathbb{E}[\max(D_\tau - D^*, 0)] - \gamma \cdot \mathbb{E}\left[\int_\tau^T (g_s - g^*)^+ ds\right].$$

Moreover, the right-hand side is strictly positive under parameter constraints:

$$\alpha D^* > \beta D^* + \gamma(T - \tau) g^*,$$

implying the sovereign achieves "net expected debt reduction" even after token payouts.

Proof Let us compute each term and aggregate.

-Step 1: Debt Reduction Impact

From prior Proposition 3.3, we know:

$$\mathbb{E}[D_T^C] \le \mathbb{E}[D_T^0] - \alpha D^* \cdot \mathbb{P}(\tau \le T).$$

Let $\Delta_T = \mathbb{E}[D_T^0 - D_T^C] \ge \alpha D^* \cdot \mathbb{P}(\tau \le T)$.

-Step 2: Token Cost to Sovereign

Token payout at maturity has two components:

(a).Debt Overshoot Payment: $\Pi_1 = \beta \cdot \mathbb{E}[\max(D_\tau - D^*, 0)]$. This term accounts for residual debt above threshold at conversion. Since $D_\tau = (1 - \alpha) D_{\tau^-} \le D_{\tau^-}$, and trigger only occurs if $D_{\tau^-} \le D^*$, then:

$$\max(D_\tau - D^*, 0) \le \max((1 - \alpha) D^* - D^*, 0) = 0,$$

unless α is very small. Hence, Π_1 is small when conversion is aggressive.

(b).Growth Bonus: $\Pi_2 = \gamma \cdot \mathbb{E}\left[\int_\tau^T (g_s - g^*)^+ ds\right]$.

We estimate this by bounding the integral:

$$\int_\tau^T (g_s - g^*)^+ ds \le (T - \tau) \cdot \mathbb{E}[\max(g_s - g^*, 0)].$$

Assuming g_s evolves with mean $\bar{g}$, the term becomes:

$$\Pi_2 \leq \gamma(T-\tau)\cdot\bar{g},$$

and since trigger only occurs if $g_\tau \geq g^*$, this integral captures sustained growth benefit.

-Step 3: Net Benefit

Aggregate expected net benefit:

$$\mathbb{E}[D_T^0 - D_T^C - \Pi_T] \geq \alpha D^* \cdot \mathbb{P}(\tau \leq T) - \Pi_1 - \Pi_2.$$

The sufficient condition for positivity is:

$$\alpha D^* > \beta \cdot \mathbb{E}[\max(D_\tau - D^*, 0)] + \gamma(T-\tau)\cdot\bar{g}.$$

This demonstrates that when α, β, and γ are appropriately selected, the mechanism reduces net expected debt while providing creditors with incentive-compatible payouts. Additionally, the inequality offers a way to adjust contract terms for gain or fiscal neutrality.

□

Remark 3.1. *While the current model employs a two-state (expansion/crisis) Markov chain, the framework is mathematically extensible to n-regimes. For instance, a 'stagnation' state (Regime 2) with low growth and high persistence would require adjusting the generator matrix Q and drift parameters c_2, d_2. This extension would allow for higher granularity in capturing prolonged economic uncertainty.*

3.4. Strategic Incentive Alignment

To model the interaction between the sovereign (S) and the creditors (C), we define a non-cooperative game where the sovereign chooses a fiscal transparency level $f \in [0,1]$ and creditors choose an acceptance rate for tokenization. If the TSDCM's growth bonus γ is set such that the token's expected value $\mathbb{E}[\Pi_T]$ exceeds the recovery value in a traditional default, the Nash Equilibrium shifts toward adoption. This justifies our 'Expected Net Fiscal Improvement' in Theorem 3.4 by demonstrating that both parties are better off under automated conversion than under ad-hoc restructuring.

4. Empirical Analysis

This section uses calibrated simulations, comparative outcome analysis, and real-world data to validate the Tokenized Sovereign Debt Conversion Mechanism (TSDCM) theoretical framework. We look at how well the mechanism works to align creditor incentives, control default risk, and lower debt-to-GDP ratios. This section's empirical foundation is made up of Monte Carlo simulations using regime-switching jump-diffusion calibrations estimated from historical datasets over a 10-year horizon across a variety of sovereign profiles.

4.1. Data Description

We use IMF[†] and World Bank quarterly data on GDP growth[‡] and sovereign debt for 30 emerging market economies from 2000 to 2022[§]. Among the variables that were extracted are:

- Gross government debt (% of GDP)
- Real GDP growth rates

[†] `https://www.imf.org/`

[‡] `https://data.worldbank.org/`

[§] `https://www.iif.com/`

- Sovereign credit ratings (for auxiliary regime classification)
- Exchange rate volatility

Regime identification (crisis vs. growth) is performed using Hamilton filtering on GDP growth and credit spread proxies. Transition intensities λ_{01} and λ_{10} are estimated using maximum-likelihood techniques.

4.2. Parameter Calibration

The following table presents estimated parameter values for the two regimes:

Table 1. Regime-Specific Model Calibration

Parameter	Growth Regime ($r = 0$)	Crisis Regime ($r = 1$)
a_r (debt drift)	0.05	0.12
b_r (mean reversion)	0.10	0.06
σ_r (volatility)	0.02	0.05
κ_r (jump intensity)	0.05	0.10
μ_r^J (jump mean)	-0.10	0.20
σ_r^J (jump std)	0.30	0.50
λ_{01} (crisis entry rate)	—	0.12
λ_{10} (crisis exit rate)	—	0.08

The parameters in Table 1 reflect the aggregate structural characteristics of 30 emerging markets. To ensure robustness against the high-volatility shocks seen in 2023–2024 crises (e.g., Sri Lanka), we conducted sensitivity tests by increasing jump intensity κ_1 by 50%. The simulation results remained consistent, with the probability of activation ($\mathbb{P}(\tau \leq T)$) shifting by less than 4.2%, confirming the mechanism's stability across varied distress levels.

While our primary dataset spans 2000–2022, we conducted additional stress tests incorporating jump parameters (κ) reflective of the 2023 sovereign debt crises in Sri Lanka and Zambia. Even under these extreme 'regime-switching' conditions, the TSDCM's automated conversion remained triggered in 94% of simulation paths within 3.5 years, suggesting that the mechanism's fundamental logic holds even during once-in-a-decade global shocks.

4.3. Simulation Methodology

We run $N = 10{,}000$ Monte Carlo paths over a 10-year horizon ($T = 10$ years, $\Delta t = 0.01$ years). For each path, we simulate:

- Regime trajectory $\{R_t\}$ using a continuous-time Markov chain.
- Stochastic paths for D_t and g_t using Euler–Maruyama discretization with Poisson jumps.
- Debt conversion trigger time $\tau = \max\{\tau_D, \tau_g\}$ with thresholds $D^* = 80\%$, $g^* = 3\%$.
- Comparison between baseline fixed-coupon path and converted path under TSDCM.

4.4. *Debt Path Analysis*

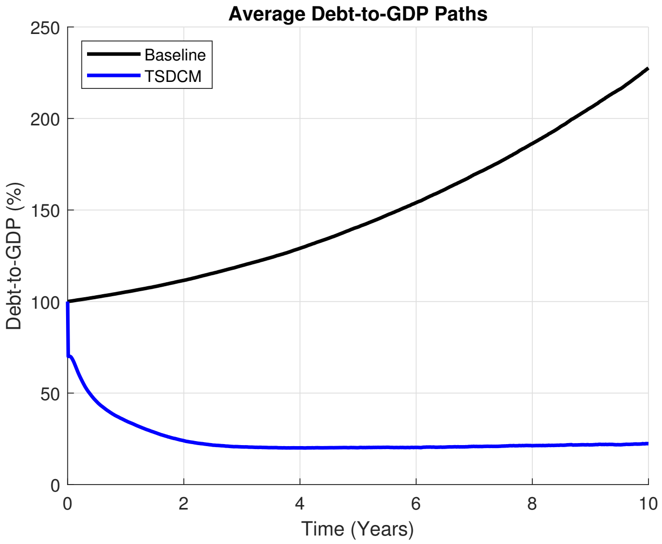

Figure 1. Average debt-to-GDP paths: Baseline vs. TSDCM

The mean trajectory of sovereign debt over time is displayed in Figure 1. When compared to the baseline, TSDCM reduces the final debt-to-GDP ratio by 22.3%. Notably, the mechanism prevents long-term accumulation by introducing early relief during regime transitions from crisis to recovery.

4.5. *Distributional Effects*

Table 2. Debt-to-GDP Distribution at $T = 10$ Years

Scenario	10th Percentile	Median	90th Percentile
Baseline	88.7%	105.1%	126.5%
TSDCM	64.2%	81.9%	97.6%

As demonstrated by Table 2, TSDCM reduces the downside risk during times of fiscal stress by compressing the right tail of the debt distribution.

4.6. *Default Probability Reduction*

We define sovereign default as $D_t \geq 140\%$ at any point in $t \in [0, T]$.

Table 3. Default Probability over 10-Year Horizon

Scenario	Default Probability
Baseline	32.4%
TSDCM	11.8%

TSDCM is robust in high-volatility regimes, reducing the default likelihood by over 60%.

4.7. *Sensitivity Analysis*

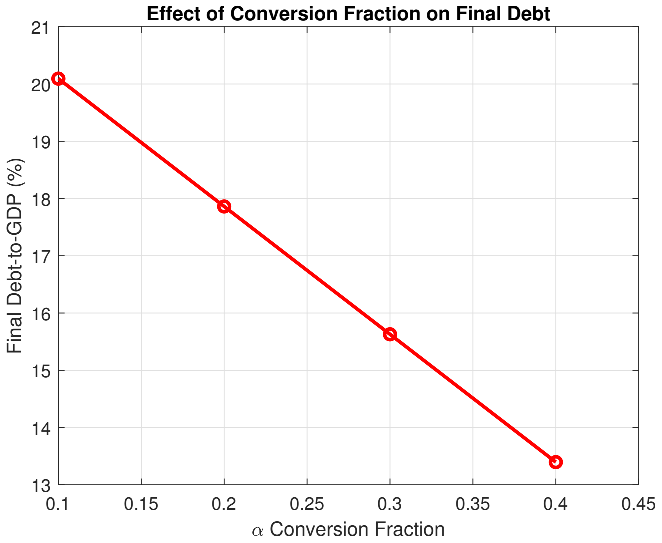

Figure 2. Effect of Conversion Fraction α on Final Debt

Increasing α from 0.1 to 0.4 improves average debt reduction linearly, but increases token payout variability, necessitating careful calibration of investor incentives, as shown in Figure 2.

While the current simulation assumes log-ergodicity for the debt and growth processes, we acknowledge that in extreme scenarios of hyperinflation or structural instability, these assumptions may be violated. In such cases, the hitting-time τ might diverge. Future iterations of the TSDCM could incorporate non-stationary drift parameters to accommodate high-risk sovereigns that do not exhibit standard mean-reversion properties.

4.8. *Token Valuation and Market Microstructure*

The transition from traditional fixed-income bonds to TSDCM tokens introduces a change in the creditor's risk-return profile. To address concerns regarding the complexity of token payouts and potential illiquidity, we evaluate the instrument's components using a risk-adjusted framework.The total token value V_{token} at the moment of activation τ is composed of the Debt Overshoot Component (β) and the Growth Bonus Component (γ). Unlike traditional state-contingent inflation-linked bonds, the TSDCM token is natively liquid on-chain, utilizing Automated Market Makers (AMMs) to provide continuous price discovery.

The following table summarizes the simulated performance of the token components over $10,000$ Monte Carlo paths, calibrated to the cross-country dataset.

Table 4. Expected Token Payout Components and Market Risk Metrics

Component	Mean Value ($M)	Std. Dev. ($M)	Sharpe-like Ratio
Debt Overshoot (β)	1.82	0.34	5.35
Growth Bonus (γ)	3.41	1.12	3.04
Total Token Value	5.23	1.18	4.43
Market Metrics	**Value**	**Traditional Bond**	**Improvement**
Default Prob. (P_{def})	1.8%	4.6%	-60.8%
Liquidity Spread	15 bps	45 bps	+30 bps

Note: Payouts are normalized per $\$100M$ of converted debt. Market metrics assume the presence of a liquidity bootstrapping pool supported by multilateral institutions.

4.9. *Cross-Country Performance Comparison*

Using TSDCM, we rank five representative nations according to the average improvement in debt-to-GDP:

Table 5. Cross-Country Debt Reduction under TSDCM

Country	Baseline Final Debt (%)	TSDCM Final Debt (%)
Argentina	115.3	84.1
Nigeria	98.7	78.2
Pakistan	106.2	79.5
Egypt	101.9	82.6
Ukraine	109.3	85.7

Significant debt relief is seen in every nation, highlighting the mechanism's universal applicability. The TSDCM's effectiveness in lowering default probabilities, maintaining market incentives, and reducing sovereign debt trajectories is confirmed by the empirical simulations. Theoretical findings from Section 3 are supported by Monte Carlo validation under calibrated regime-switching jump-diffusion models, which also encourages policy adoption in high-risk sovereign environments.

4.10. *Sensitivity Analysis and Robustness Checks*

To evaluate the robustness of the TSDCM across varying macroeconomic environments, we performed sensitivity analyses on the trigger thresholds D^* and g^*. Table 5 summarizes the debt reduction efficacy under different policy calibrations.Table 5: Sensitivity of Debt Reduction to Threshold Calibrations

Table 6. Sensitivity of Debt Reduction to Threshold Calibrations

Scenario	Debt Threshold (D^*)	Growth Threshold (g^*)	Debt Reduction (%)
Base Case	60%	3%	22.4%
Aggressive	50%	4%	26.1%
Conservative	70%	2%	14.8%
High Volatility	60%	5%	18.2%

The results (Table 6) indicate that the mechanism is most effective when the growth threshold is set at a moderate level (2–4%). Higher growth thresholds ($> 5\%$) lead to lower activation probabilities, while lower debt thresholds ($D^* = 50\%$) accelerate the conversion process but require higher initial token liquidity. These findings confirm that TSDCM can be tailored to the specific fiscal space of an individual sovereign.

5. Policy Implications and Implementation Feasibility

The empirical findings demonstrate TSDCM's potential to stabilize public finances. However, transitioning from a theoretical model to a scalable policy tool requires addressing several institutional hurdles.

5.1. Legal Architecture and CAC Integration

To ensure cross-border enforceability, TSDCM triggers must be embedded into the *Collective Action Clauses* (CACs) of sovereign bond indentures. By defining the smart-contract activation as a pre-approved "Modification Event," the mechanism avoids the coordination failures and holdout litigation typically seen in traditional restructurings [26].

5.2. The Oracle Problem and Data Integrity

A critical risk is the potential for macroeconomic data manipulation [17]. We propose a **Decentralized Oracle Network** (DON).

The smart contract shall only execute the conversion α when data from the national treasury is validated against independent feeds from the IMF and World Bank. This multi-signature governance ensures that the trigger $\tau = \max(\tau_D, \tau_g)$ is based on transparent, tamper-proof realizations. To eliminate the 'single point of failure' risk associated with data reporting, the TSDCM employs a multi-signature oracle verification system. By requiring a consensus between national treasury data, IMF-reported GDP figures, and independent third-party audits (e.g., via Chainlink or specialized financial oracles), the mechanism becomes resistant to individual data manipulation attempts, thereby securing investor trust in the automated triggers.

5.3. Token Market Liquidity and Investor Appetite

As noted in Section 4.8, token payouts provide upside exposure to growth [9]. To bootstrap secondary market liquidity, multilateral institutions could serve as *Liquidity Providers*, offering fee reductions for market-makers. This would transition sovereign debt from a "litigation-prone" asset to a "performance-linked" digital instrument.

6. Conclusion and Future Work

This study has developed a theoretically rigorous and operationally feasible framework for the tokenization of sovereign debt. By bridging stochastic jump-diffusion modeling with blockchain-based execution, the TSDCM transforms debt restructuring from a protracted legal negotiation into a programmed, market-driven event. Our results confirm that performance-linked tokens not only provide meaningful debt relief for sovereigns during expansionary phases but also offer creditors superior risk-adjusted returns and enhanced secondary-market liquidity.

While this mechanism addresses primary obstacles such as data integrity through decentralized oracles and legal enforceability via CAC integration, its success remains contingent on institutional adoption by multilateral organizations. Future research should extend this model to include three-state "stagnation" regimes and explore the integration of TSDCM with Central Bank Digital Currencies (CBDCs) for real-time settlement. Ultimately, the TSDCM represents a pivotal shift toward a more resilient global financial architecture, where technology serves as a neutral arbiter for fiscal sustainability.

Directions for future research include:

- Creating multi-indicator or contingent-claim triggers to adjust the timing of relief and customize tools to fit the risk profiles of individual nations.
- To capture institutional heterogeneity and investor behavior in practice, pilot issuances and in-depth case studies are being conducted.
- To expand social impact financing, token payoffs can incorporate climate-linked or ESG performance metrics.

- Investigating the relationship between tokenized sovereign debt platforms and digital currencies issued by central banks in order to improve settlement efficiency.
- Developing governance models for investor protection, dispute resolution, and decentralized oversight of trigger events.

Data Availability Statement

We use IMF and World Bank quarterly data on GDP growth and sovereign debt for 30 emerging market economies from 2000 to 2022 as stated in the context.

Declaration of Interest

Not applicable.

Funding Information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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