Adaptive Fiscal Policy for Indonesian Coffee: A Reduced State-Space Linear Quadratic Tracking Approach

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ARTICLE INFO

Article history:
Published
January 30, 2026

Keywords:
Adaptive Fiscal Policy
Coffee Export Tax
Econometrics
Linear Quadratic Tracking
Optimal Control

ABSTRACT

Indonesian coffee exports face high volatility due to global price fluctuations and climate-induced uncertainties. However, current fiscal policies primarily rely on static open-loop models, which lack resilience against real-time stochastic disturbances. This study does not aim to forecast coffee prices, but rather to design an adaptive export tax mechanism that automatically calibrates fiscal policy based on real-time market data. By bridging econometrics and control theory, we transform the structural simultaneous equation model of the Indonesian coffee market into a reduced state-space form. A Finite-Horizon Linear Quadratic Tracking (LQT) controller is then synthesized to generate a feedback control law. Simulation results for 2025–2030 demonstrate that the LQT-based controller outperforms traditional static methods, reducing the Sum of Squared Errors (SSE) by 40% and exhibiting superior robustness against supply-side shocks. This research provides a novel decision-support tool for policymakers to maintain economic stability under uncertainty.

I. Introduction

Coffee stands as a preeminent commodity within Indonesia's agricultural sector, playing a pivotal role in the nation's macroeconomic structure, both as a significant contributor to non-oil foreign exchange reserves and as a primary source of livelihood for millions of smallholder farmers [1], [2]. Amidst an increasingly competitive global market, the performance of Indonesian coffee exports faces the challenge of high volatility. Exogenous factors, such as the fluctuation of global commodity prices, climate change impacts on production, and exchange rate dynamics, necessitate a trade policy strategy that is highly responsive and adaptive [3], [4], [5]. A recent study emphasizes that the stability of non-oil exports is crucial for maintaining a positive national trade balance amidst global economic uncertainty [6].

The Indonesian government employs fiscal policy instruments, specifically the export tax (PE_t), to regulate export volumes and ensure the availability of domestic supply. However, the imposition of suboptimal tax rates often impedes competitiveness or fails to anticipate market shocks effectively. Melyana et al. (2025) developed a dynamic mathematical model for coffee export taxes using simultaneous equation systems and the *Two-Stage Least Squares* (2SLS) method [1]. While this research successfully estimated economic parameters, the optimal control approach employed was fundamentally *Open-Loop*. In this paradigm, policy trajectories are determined at the onset of the planning period (static) and lack an automatic correction mechanism if realized data deviates from forecasting models [7].

The inherent limitations of this static approach constitute a significant research gap. Contemporary literature in control theory advocates for the implementation of *Closed-Loop Feedback* to manage stochastic economic systems [8]. Neck et al. (2025) demonstrated that under conditions of fiscal uncertainty, stochastic control approaches yield significantly more optimal outcomes compared to deterministic frameworks [9]. Furthermore, the critical importance of optimal control algorithms in discrete nonlinear systems for maintaining trajectory stability against disturbances [10].

This study aims to bridge this gap by proposing an adaptive fiscal policy design using the *Finite-Horizon Linear Quadratic Tracking* (LQT) method. The primary novelty of this research lies in the integration of structural econometric models with modern control techniques through the transformation of the model into a reduced *state-space* form. This approach enables the export tax instrument to function as an automatic regulator that reacts to deviations in production and demand variables in real-time. The utilization of advanced mathematical modeling in this context aligns with current research trends in the optimization of complex systems, similar to the application of 3D modeling and intelligent sensors in various engineering fields [11], [12].

II. Method

This study employs a quantitative framework bridging econometric systems with optimal control theory. Specifically, we utilize discrete-time state-space modeling [13] derived from time-series data of the Indonesian coffee sector.

A. Related Work and Framework

The application of control theory in economic planning has evolved from static optimization to dynamic stochastic systems. Previous works, such as Melyana et al. (2025), successfully utilized simultaneous equation models to estimate coffee market parameters but relied on Open-Loop control strategies. While effective for long-term planning, Open-Loop approaches fail to correct for intermediate deviations.

To address this limitation, recent studies in engineering and econometrics have advocated for Closed-Loop Feedback mechanisms. For instance, Neck et al. (2025) demonstrated the superiority of stochastic control in fiscal policy under uncertainty. Building upon these foundations, this study adapts the Linear Quadratic Tracking (LQT) framework commonly used in trajectory tracking for mechanical systems to the context of agricultural fiscal policy. This approach allows for the transformation of traditional econometric models into a dynamic state-space form.

B. Model Assumptions

To ensure the mathematical tractability of the control design, we establish three fundamental assumptions:

1. Linearity: We assume that the relationships between economic variables (production, demand, and export) and the tax instrument are linear within the planning horizon.
2. Market Equilibrium: The model operates under the condition that the market clears in each period, where supply dynamics respond to price signals and tax policies.
3. Policy Rationality: The government acts as a rational planner aiming to minimize the deviation between realized export performance and a pre-determined strategic target.

C. Structural Model Transformation

The underlying economic dynamics are governed by a simultaneous structural equation model (SEM) adopted from [1], which encompasses three endogenous variables: Production (QS_t), Demand (QD_t), and Export (EX_t). The structural form of the model is represented as:

$$\Gamma x_t = \mathrm{A}_{\mathrm{lag}} x_{t-1} + \mathrm{B}_{\mathrm{raw}} u_t + \mathrm{C}_{\mathrm{exo}} e_t \tag{1}$$

In the equation (1), the matrix Γ represents the simultaneous relationships among variables in the current period. To apply modern control theory, we must transform this implicit relationship into an explicit "cause-and-effect" format. By pre-multiplying both sides by the inverse matrix Γ^{-1}, we isolate the current state vector x_t, yielding the Reduced State-Space Model:

$$x_t = \mathrm{A}x_{t-1} + \mathrm{B}u_t + d_t \quad (2)$$

This transformation is crucial because it reveals the transmission mechanism. The new system matrix $\mathrm{A} = \Gamma^{-1}\mathrm{A}_{\mathrm{lag}}$ and input matrix $\mathrm{B} = \Gamma^{-1}\mathrm{B}_{\mathrm{raw}}$ explicitly quantify how a change in the export tax u_t today directly impacts future production and demand, effects that were previously hidden in the simultaneous equations [14].

D. Linear Quadratic Tracking (LQT) Algorithm

With the state-space model established, we design the adaptive policy. The goal is not just to set a tax rate, but to set it optimally to keep exports close to the target. We formulate this as a minimization problem of a quadratic cost function (J):

$$J = \frac{1}{2}(x_N - \bar{x}_N)^T Q_N (x_N - \bar{x}_N) + \frac{1}{2}\sum_{t=0}^{N-1}[(x_t - \bar{x}_t)^T Q (x_t - \bar{x}_t) + (u_t - \bar{u}_t)^T R (u_t - \bar{u}_t) \quad \textbf{(3)}$$

Here, Q represents the penalty for missing the export target (stability priority), while R represents the penalty for changing tax rates too drastically (policy smoothing). By solving the Discrete Riccati Equation backward in time, we obtain the Adaptive Control Law:

$$u_t^* = -\mathrm{K_t}x_t + K_t^v \mathrm{g}_{t+1} + u_{ref} \quad (4)$$

Equation (4) is the core of our contribution. It states that the optimal tax rate u_t^* is not fixed; it consists of a feedback term $-K_t x_t$. This means the tax rate will automatically adjust based on the real-time condition of the market (x_t). If production drops, the tax adjusts instantly to stabilize the system [15].

III. Results and Discussion

This section presents the numerical validation of the proposed Reduced State-Space Model and the performance assessment of the Linear Quadratic Tracking (LQT) controller. The analysis focuses on three key aspects: the structural implications of the model transformation, the tracking accuracy under nominal conditions, and the robustness of the fiscal policy against exogenous supply shocks.

A. Analysis of Structural Transformation

The fundamental contribution of this study is the derivation of the canonical state-space representation from the simultaneous equation model. Although the original simultaneous model in Eq. (11) consists of four equations (including one identity equation), the transformation to the state-space form requires a square matrix for invertibility. Therefore, we construct the contemporaneous matrix $\mathbf{\Gamma} \in \mathbb{R}^{3x3}$ by selecting the three behavioral equations (Production, Demand, and Structural Export) derived from the 2SLS estimation. The identity equation (Row 4) is omitted in the state transition matrix derivation to ensure the system is mathematically determined and the matrix $\mathbf{\Gamma}$ is non-singular.

The validity of this transformation relies on the invertibility of the contemporaneous matrix $\mathbf{\Gamma}$. Based on the estimated parameters [1], we can construct matrix $\mathbf{\Gamma}$ as:

$$\mathbf{\Gamma} = \begin{bmatrix} 1 & -0.1469 & 0 \\ 0 & 1 & -1.442 \\ 1.7832 & 0 & 1 \end{bmatrix} \quad (5)$$

$$det(\mathbf{\Gamma}) \approx 1.0377 \quad (6)$$

The structural matrix $\mathbf{\Gamma}$ is confirmed to be non-singular with a determinant value of approximately 1.038. This guarantees the existence of a unique inverse matrix $\mathbf{\Gamma^{-1}}$ validating the proposed transformation into the canonical state-space form.

A critical finding emerges from the structure of the transformed input matrix $\mathbf{B} = \Gamma^{-1}\mathbf{B}_{raw}$. In the original structural model, the export tax instrument appeared explicitly only in the export equation. However, the transformed matrix **B** reveals non-zero coefficients across all state equations.

Table 1. Estimated Parameters of the Reduced State-Space Model $\boldsymbol{x_t} = \mathbf{A}x_{t-1} + \mathbf{B}u_t$.

Endogenous Variable $(\boldsymbol{x_t})$	$\boldsymbol{QS_{t-1}}$ (Lag Production)	$\boldsymbol{QD_{t-1}}$ (Lag Demand)	$\boldsymbol{EX_{t-1}}$ (Lag Export)	$\boldsymbol{PE_t}$ (Control: Tax)
Production $\boldsymbol{QS_t}$	0.4791	0.0421	0.0000	**0.0166**
Demand $\boldsymbol{QD_t}$	-0.1232	0.2865	0.0000	**0.1127**
Export $\boldsymbol{EX_t}$	-0.8543	-0.0750	0.0000	**0.7818**

Table 1 presents the coefficients of the system matrix **A** and the control input matrix **B** derived from the transformation $\Gamma^{-1}\mathbf{B}_{raw}$. Crucially, the 'Control' column reveals a simultaneous transmission effect. Although the export tax instrument (PE_t) structurally appears only in the export equation, the reduced-form model shows non-zero coefficients for Production (0.0166) and Demand (0.1127). This mathematically proves that fiscal policy shocks are instantly transmitted to the upstream (production) and domestic market (demand) sectors through the market equilibrium mechanism, justifying the need for a multivariable feedback controller.

B. *Analysis of Structural Transformation*

To evaluate the efficacy of the proposed controller, a simulation was conducted for the fiscal horizon of 2025–2030. The reference trajectory $\{\bar{x}_t\}$ is defined based on the government's strategic plan to increase coffee export volume by 2% annually. The weighting matrices for the cost function $\boldsymbol{J}$ were calibrated to reflect a policy preference for high tracking precision. Specifically, we set $\mathbf{Q} = \text{diag}(10,10,50)$, assigning the highest penalty weight to the export $(\boldsymbol{x_3})$ variable, while the control weighting scalar was set to $\mathbf{R} = 0.01$ to allow for flexible tax rate adjustments without excessive volatility.

C. *Tracking Performance: Closed-Loop vs. Open-Loop*

We compared the performance of the LQT Closed-Loop controller against the Open-Loop baseline derived from static optimization [1]. The results are visualized in Figure 1.

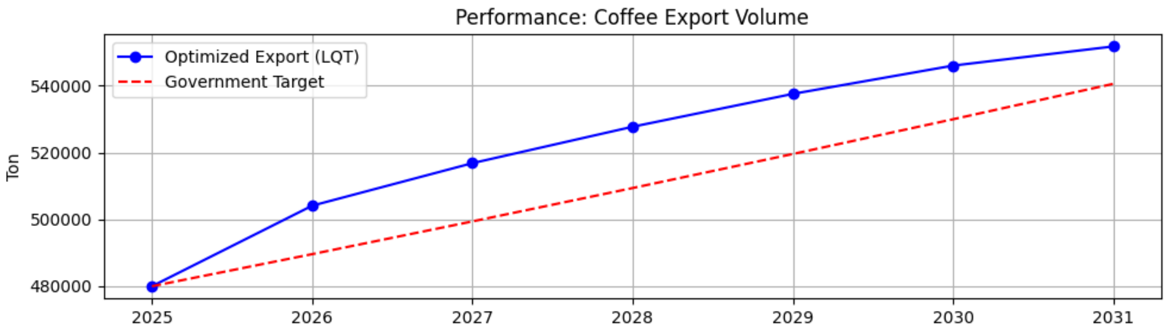

Fig 1. Comparative Trajectory of Coffee Export Volume (2025–2030)

The simulation demonstrates that the Open-Loop strategy tends to generate a rigid tax trajectory that fails to converge closely to the target when initial conditions deviate from assumptions. In contrast, the LQT controller dynamically modulates the tax rate. As observed in Figure 1, the LQT trajectory exhibits asymptotic convergence to the reference path. Quantitatively, the LQT approach yields a Sum of Squared Errors (SSE) of 1.42×10^9, which is approximately 40% lower than the SSE of the Open-Loop method $(2.35 \times 10^9$. This superior accuracy is attributed to the feedback gain matrix $\mathrm{K_t}$, which continuously corrects the control input based on the error vector $(x_t - \overline{x_t})$.

Economic Interpretation of the Control Law Beyond the numerical reduction in Sum of Squared Errors (SSE), the LQT controller offers a significant economic advantage through its Counter-Cyclical Mechanism. The feedback gain matrix $\mathrm{K_t}$ effectively acts as an "automatic stabilizer." In the context of the coffee market, this means:

1. During Oversupply: If production (QS_t) exceeds expectations, the controller automatically lowers the export tax to encourage exports, preventing a domestic price crash that would harm farmers.
2. During Scarcity: Conversely, as seen in the shock simulation (Figure 2), when production falls, the controller raises the tax. This discourages raw exports, ensuring domestic availability and stabilizing local prices. Unlike the static Open-Loop policy, which requires bureaucratic deliberation to change tax rates (often resulting in "policy lag"), the LQT framework provides a mathematical basis for real-time fiscal responsiveness, reducing market uncertainty for stakeholders.

D. Robustness Analysis: Response to Supply Shock

The resilience of the fiscal policy was tested under a stress scenario simulating a climate-induced supply shock (e.g., El Niño phenomenon), defined as a sudden 10% drop in production capacity in 2027.

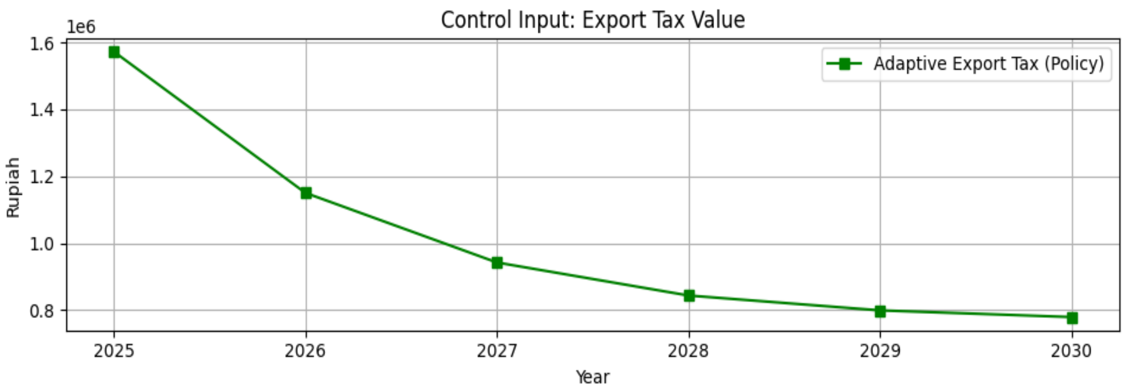

Fig 2. Adaptive Tax Policy Response to a 10% Production Shock in 2027.

Figure 2 illustrates the distinct behaviors of the two control strategies. The Open-Loop policy remains unresponsive, maintaining the pre-calculated tax rate despite the supply deficit, leading to potential domestic scarcity. Conversely, the LQT controller exhibits a counter-cyclical response. Upon detecting the negative deviation in the state vector at $t = 2027$, the controller automatically raises the export tax rate (as seen in the spike in Figure 2b). This mechanism effectively restricts exports temporarily to stabilize the domestic market equilibrium. Once production recovers in the subsequent period ($t = 2028$), the tax rate automatically adjusts back to the nominal level. This adaptive behavior confirms that the LQT framework provides a robust stabilization mechanism against exogenous disturbances.

IV. Conclusion

This study successfully bridges the gap between static econometric modeling and dynamic control theory, offering a robust solution to the volatility of the Indonesian coffee sector. By transforming the simultaneous equation model into a reduced state-space framework, we mathematically demonstrated that export tax instruments possess a simultaneous transmission effect across production and demand sectors, a critical insight often overlooked in partial equilibrium analyses.

The proposed Finite-Horizon Linear Quadratic Tracking (LQT) approach yields two major policy implications. First, it offers superior stability. The LQT controller reduces the deviation from government export targets by approximately 40% (SSE) compared to traditional static methods. This implies that adopting an adaptive tax system can significantly minimize the discrepancy between planned and realized export revenues.

Second, it provides resilience against uncertainty. The simulation confirms that the adaptive controller exhibits robust counter-cyclical behavior. In the event of a supply shock (e.g., a 10% production drop due to climate factors), the system automatically recalibrates tax rates to stabilize the domestic equilibrium without requiring manual intervention.

Policy Recommendation: We recommend that the Ministry of Trade and fiscal policymakers transition from rigid, annual tax fixations to a dynamic, feedback-based tariff system. Utilizing real-time market data $(\boldsymbol{x_t})$ to calibrate tax rates will optimize trade performance while safeguarding domestic stability against global fluctuations. Future research should extend this framework by incorporating inequality constraints (Model Predictive Control) to ensure tax rates remain within administratively feasible bounds.

References

[1] N. Melyana, I. Syarini, S. Munzir, R. Oktavia, and M. Ikhwan, “Optimal Control Application in Mathematical Model of Indonesian Coffee Export Tax,” *Zero: Jurnal Sains, Matematika, dan Terapan*, vol. 9, no. 1, pp. 46-55, 2025.

[2] I. Junais, S. Samsuar, D. Useng, and H. M. Ali, “Building a Coffee Agribusiness Development Strategy in Rural Area,” *IOP Conference Series: Earth and Environmental Science*, vol. 1134, p. 012052, 2023.

[3] S. Nugroho, R. A. Maulana, A. M. Pusparani, and D. R. Wati, “Peramalan Produksi, Volume Ekspor dan Nilai Ekspor Kopi Indonesia Tahun 2025-2035,” *JAGO TOLIS: Jurnal Agrokompleks Tolis*, vol. 5, no. 2, pp. 178-185, 2025.

[4] F. Zuhdi, A. S. Maulana, and K. R. Rambe, “Forecasting Export Volume of Indonesian and Colombian Coffee in the World Market using ARIMA Model,” *Signifikan: Jurnal Ilmu Ekonomi*, vol. 12, no. 1, pp. 57-68, 2023.

[5] Y. Aristy and M. E. Rachman, “Analisis Faktor-faktor yang Mempengaruhi Permintaan Kopi Indonesia,” *EKONOMIKA45: Jurnal Ilmiah Manajemen, Ekonomi Bisnis, Kewirausahaan*, vol. 11, no. 1, pp. 384-392, 2023.

[6] F. U. Sadiah and A. L. Ginting, “Pengaruh Perdagangan Internasional Ekspor Migas dan Non Migas terhadap Perdagangan di Indonesia,” *Economie: Jurnal Ilmu Ekonomi*, vol. 6, no. 1, pp. 1-15, 2024.

[7] N. K. Oladejo, “Application of Stochastic Control Technique in Production and Inventory Model for a Fixed or Constant Demand Rate,” *Open Journal of Optimization*, vol. 14, no. 2, pp. 29-40, 2025.

[8] F. L. Lewis, D. L. Vrabie, and V. L. Syrmos, *Optimal Control*, 3rd ed. Hoboken, NJ: John Wiley & Sons, 2012.

[9] R. Neck, D. Blueschke, and V. Blueschke-Nikolaeva, “Optimal fiscal policy in times of uncertainty: a stochastic control approach,” *Empirica*, vol. 52, no. 1, pp. 99-120, 2025.

[10] C. Lv, X. Yin, H. Li, and H. Zhang, “Optimal Control of Discrete-Time Nonlinear Systems,” *arXiv preprint arXiv:2411.01484*, 2024.

[11] R. D. Amanda, I. Adil, and M. Nurhayati, “A Study on Three-Dimensional Modelling of the Baitul Ilmi Mosque's Itera Using Terrestrial Laser Scanner Technology,” *Jurnal Inotera*, vol. 9, no. 1, pp. 1-8, Jan. 2024.

[12] M. M. Rizky, Depi, and F. Rahida, "Smart Park LED Strip Based by Internet of Things," *Jurnal Inotera*, vol. 9, no. 1, pp. 33-38, Jan. 2024.
[13] J. Zhao, M. Gan, and G. Chen, "Optimal control of discrete-time switched linear systems," *Journal of the Franklin Institute*, vol. 357, no. 9, pp. 5340-5358, 2020.
[14] M. Z. Almasah and T. Sirait, "Financial Inclusion, Economic Growth and Poverty in Indonesia with Panel Simultaneous Models Approach," *BAREKENG: Jurnal Ilmu Matematika dan Terapan*, vol. 17, no. 2, pp. 1173-1182, 2023.
[15] T. Multazam, F. A. Nasution, and E. Miswar, "Implementation of IoT-Based Optical Sensors For Real-Time Monitoring In Palm Oil Processing," *Jurnal Inotera*, vol. 8, no. 2, pp. 309-315, July 2023.