Discrete Taylor Rules*

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Abstract

I introduce a discrete Taylor rule that mirrors the institutional practice of adjusting policy rates in 25-basis-point steps. Re-estimating several examples from the literature shows that this rule reduces residuals by up to one-third, suggesting smaller monetary policy shocks than previously estimated. Embedding the rule in a New-Keynesian model and additionally restricting interest rate adjustments to two predetermined dates per quarter yields further insights. First, impulse responses change substantially, exhibiting kinks and delayed returns to steady state. These effects are heterogeneous across the output gap and inflation and with respect to the shock size. Second, in a simulated U.S. business cycle, the interest rate deviates on average by 33 basis points from the linear-rule benchmark, and discreteness accounts for 1.95% of output-gap variance. In contrast, infrequent rate adjustments reduce volatility by making monetary policy more active on average.

Keywords: Monetary policy, Taylor rule, New-Keynesian models

JEL Classification: E43, E47, E52, E58, E32

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1 Introduction

The Taylor rule is a key ingredient in any New-Keynesian model used in research and by central banks and other institutions. Since its first specification by Taylor (1993), researchers have proposed various extensions. These include making it forward- or backward-looking (Judd and Rudebusch, 1998; Clarida et al., 2000), introducing persistence (Judd and Rudebusch, 1998; Qin and Enders, 2008), and accounting for nonlinearities (Martin and Milas, 2004; Cukierman and Muscatelli, 2008; Castro, 2011; Qin and Enders, 2008).

This paper contributes to the literature by relaxing two assumptions shared by the original Taylor rule and its extensions. First, existing versions of the Taylor rule are continuous. Second, they determine the interest rate in every single period. Both assumptions are inconsistent with observed monetary policy. In practice, central banks adjust policy rates in fixed increments, typically multiples of 25 basis points, and only on a limited number of predetermined dates each year. Figure 1 illustrates these features. Exceptions occur only under extraordinary circumstances. For instance, the Federal Open Market Committee (FOMC) met more frequently during the first weeks of the Covid-19 pandemic in the United States (Thornton and Wheelock, 2025), and the federal funds rate was reset between scheduled meetings following the September 11, 2001 attacks (Piazzesi, 2005).

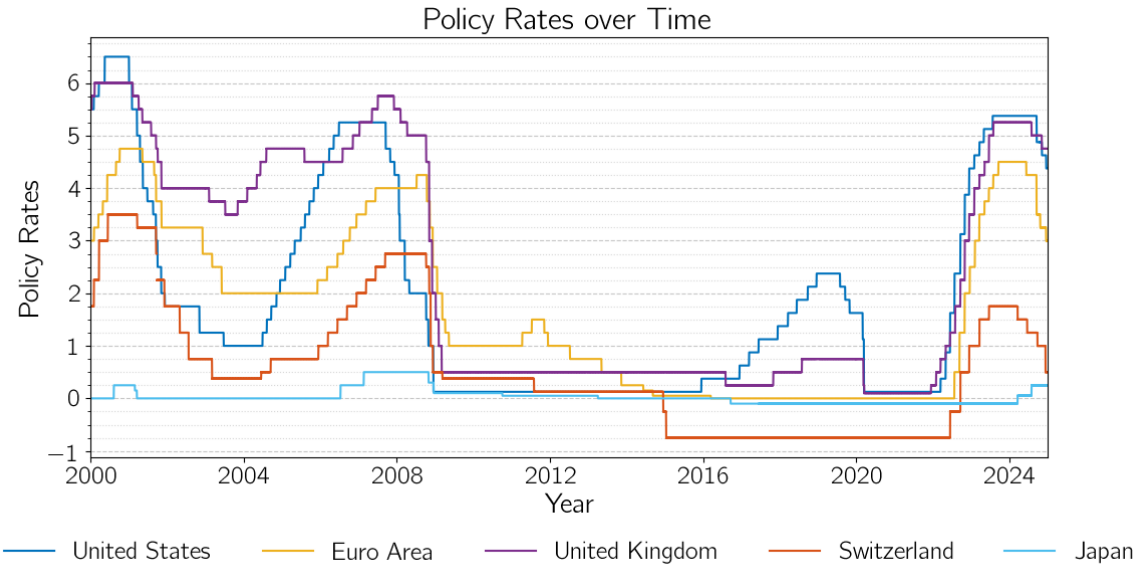


Figure 1: Discrete policy rates in major currency areas, 2000–2024. Source: BIS (2025).

The fixed interest rate step size and the infrequent central bank decisions make Taylor rules discrete in two respects—first, as interest rates are picked from a discrete set, and second, as interest rates are updated at discrete points in time.

I study the first property by replicating influential Taylor rule estimations using a specification constrained to a discrete set of interest rates. For the U.S., the euro area, and

Japan during different time periods from 1979 to 2025, I show that this modification improves the fit for the target rate and, more recently, also for the market rate, reducing average residuals by up to one-third. Based on this result, I argue that estimating linear rules may lead to an overestimation of monetary policy shocks, including deviations from the linear rule that are fully anticipated by agents as they reflect the constraint on monetary policy to stay on a discrete grid.

Next, I incorporate discrete interest rate steps and infrequent interest rate adjustments into a New-Keynesian DSGE model. After deriving the solution of the model, I calibrate monetary policy such that the central bank adjusts the interest rate twice per quarter and in increments of 25 basis points, reflecting the institutional setting of the U.S. and the euro area. The period length corresponds to one day, which allows distinguishing between periods with and periods without interest rate decisions.

The model is then used to study the response to MIT shocks. For this exercise, impulse response functions are decomposed, which enables me to quantify the extent to which variables are driven by discrete interest rates on the one hand and infrequent interest rate decisions on the other hand. I find that discreteness has a significant effect on all variables' responses, whereas infrequency has substantial effects only on the interest rate and only prior to the first central bank decision following the shock. The sign of the discreteness component switches over time for all variables, and it affects the output gap and inflation differently, resulting in U-shaped impulse responses for the output gap and a roughly linear—rather than geometric—decay of the inflation response. Because the effect of discreteness does not scale linearly in the shock size, impulse response functions are inhomogeneous with respect to the shock size, which constitutes a violation of a standard property of linearized New-Keynesian models.

Finally, I estimate a subset of model parameters using U.S. data. Based on the estimated parameters, I simulate a business cycle to quantify the effects of discreteness and infrequency in practice. I find that monetary policy is substantially altered, with an average gap of 33 basis points between my model and the linear benchmark. In particular, discreteness translates into the real economy, accounting for 2% of output-gap variance while significantly reducing inflation variance, which is consistent with the heterogeneous effects identified in impulse responses. In contrast, infrequency rather reduces the volatility of both variables, as it makes monetary policy more active on average.

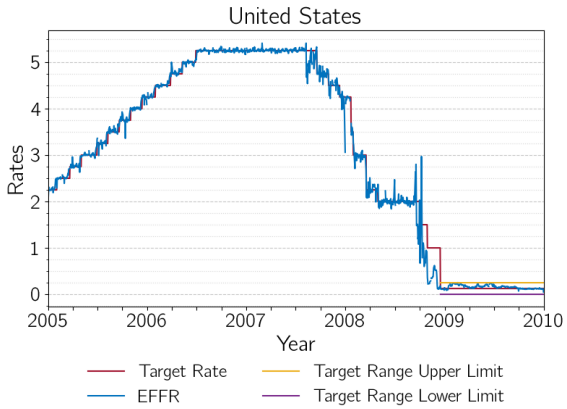
Despite extensive literature on modifications to the Taylor rule, the discrete nature of policy rates has been explicitly addressed in only few papers. First, Piazzesi (2005) specifies a policy rule to study the interaction between the Federal Open Market Committee (FOMC) decisions and the yield curve. She accounts for the fact that the target rate changes are multiples of 25 basis points when estimating the policy rule. Additionally, she incorporates fixed intervals between FOMC meetings but assigns a small probability to rate adjustments between meeting dates, motivated by a few empirical examples. She

shows that the FOMC's decision are particularly driven by two-year bond yields, and that her rule performs better than standard interest rate rules like the one proposed by Taylor (1993). As she computes the expected value of the target rate, fitted values remain continuous. Second, Scotti (2011) proposes a conditional bivariate ordered probit model to estimate the probabilities of discrete target rate changes for the U.S. and the euro area. Third, Dueker (2002) and Dueker and Rasche (2004) examine the effect of discrete interest rate changes in VAR models. A common approach in the time-series literature is to use monthly or quarterly averages of the federal funds rate to generate observations. This can misidentify the timing of shocks: if average rates differ across two periods, a shock may be attributed to the later period even when the adjustment occurred earlier and the end-of-period rate equals the later period's average. The papers propose methods to correct for this issue in VARs.

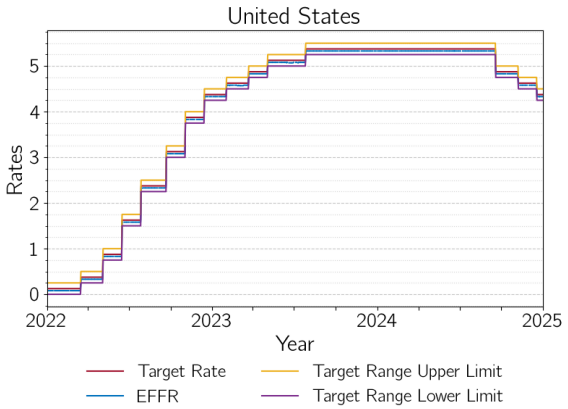
Relative to the existing literature, the contribution of this paper is twofold. First, it assesses how common interest rate rules from the literature perform when discreteness is added, leaving all else equal, and shows that discrete rules usually generate smaller residuals. Second, the paper is the first to explicitly incorporate discrete and infrequent interest-rate setting into a general equilibrium model, analyzing the theoretical implications and quantifying the effects of both features on impulse responses and the business cycle in a New-Keynesian framework.

One reason why discrete rates were studied so rarely in the existing literature may be that the accurate translation of discrete target into market rates is a relatively recent phenomenon. Before 2010, overnight market rates were highly correlated with but substantially more volatile than target rates, yielding significant deviations around the target. The same, albeit with much lower volatility than before 2010, characterizes the short period of non-zero interest rates in the U.S. from 2017 until 2020. Only since target rates have returned to positive levels in 2022, overnight market rates have tracked their movements precisely and are clearly discrete. The reason underlying this trend towards lower volatility of market rates is the supply of ample reserves, a policy beginning in 2008 with large-scale asset purchases and officially confirmed in 2019 (Federal Open Market Committee, 2019; McGowan and Nosal, 2020). Figure 2 shows the difference between pre-ZLB and post-ZLB periods for the U.S. and the euro area. The same relation holds for the United Kingdom and Switzerland (see Figure 12 in the Appendix).

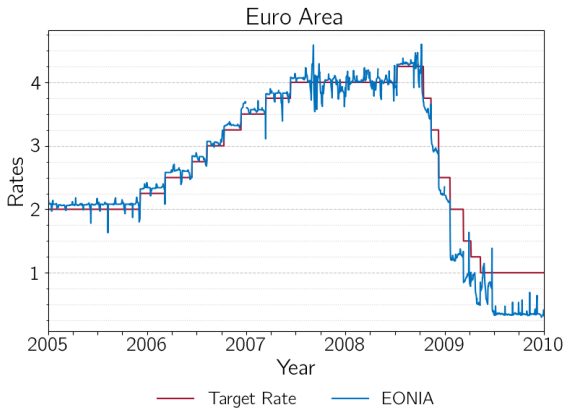
The remainder of this paper is organized as follows. Section 2 studies the empirical performance of estimated discrete Taylor rules in contrast to their linear counterparts. Section 3 sets up a simple New-Keynesian model that accounts for both discrete timing of target rate adjustments and discrete rate steps. In Section 4, I analyze the model's response to MIT shocks. In Section 5, I estimate a subset of model parameters on U.S. data and analyze a simulated business cycle. Section 6 concludes.



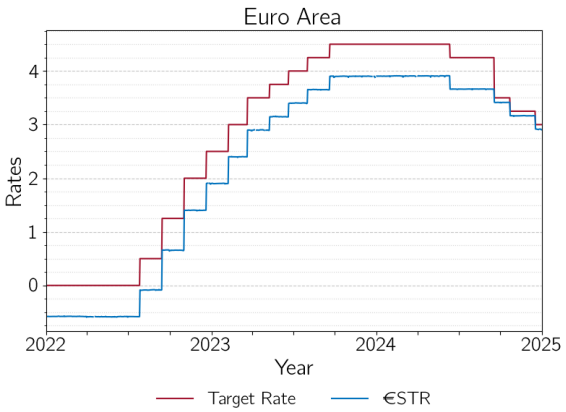
(a) United States, 2005–2010. Sources: BIS (2025), Federal Reserve Bank of New York (2025), Board of Governors of the Federal Reserve System (US) (2025b), Board of Governors of the Federal Reserve System (2025a).



(b) United States, 2022–2025. Sources: BIS (2025), Federal Reserve Bank of New York (2025), Board of Governors of the Federal Reserve System (US) (2025b), Board of Governors of the Federal Reserve System (2025a).



(c) Euro Area, 2005–2010. Sources: BIS (2025), European Central Bank (2025a).



(d) Euro Area, 2022–2025. Sources: BIS (2025), European Central Bank (2025b). €STR replaced EONIA in 2019 (Nicoloso and Tsonchev, 2019).

Figure 2: Target rates and average overnight market rate indices for the U.S. and the euro area. Since the end of the zero-lower-bound period, market rates are discrete.

2 Empirical Performance of Discrete Taylor Rules

In this section, I assess the empirical performance of discrete Taylor rules by re-estimating linear Taylor rules from the literature and estimating their discrete counterparts. Here, not only the specifications but also the time periods and areas for which the rules are estimated are adopted from the benchmark papers. Comparing residuals, I find that discrete rules consistently yield lower mean absolute errors when explaining target rates, with lower mean squared errors in three out of four cases.

I then confirm this result for the recent post-ZLB period in the U.S. by replicating two setups based on monthly and quarterly data for this period. Importantly, the findings now also hold for market rates, as they have been equally discrete in this period.

2.1 Estimation Approach

Throughout this section, denote by X_t the $(N \times 1)$ vector of $N-1$ variables plus a constant. The discrete Taylor rule $\mathcal{D}(X_t, \alpha_{\mathcal{D}})$ approximates the linear Taylor rule $\ell(X_t, \alpha_{\mathcal{D}})$ on a grid $I = \{\dots, -0.5, -0.25, 0, 0.25, 0.5, \dots\}$ that contains all multiples of 0.25. Formally,

$$\mathcal{D}(X_t, \alpha_{\mathcal{D}}) = \arg\min_{i_t^\star \in I} \left(i_t^\star - \ell(X_t, \alpha_{\mathcal{D}})\right)^2. \tag{1}$$

Moreover,

$$\ell(X_t, \alpha_{\mathcal{D}}) = \alpha_{\mathcal{D}} X_t,$$

i.e., $\ell(X_t, \alpha_{\mathcal{D}})$ is linear in all of its arguments, where $\alpha_{\mathcal{D}}$ is the $(1 \times N)$ vector of linear coefficients.

In the following, I estimate the coefficients of the linear rule and of its discrete approximation separately. For the linear rule, let α_ℓ denote the vector of coefficients. The regression model is specified as

$$i_t = \ell(X_t, \alpha_\ell) + \varepsilon_t^\ell = \alpha_\ell X_t + \varepsilon_t^\ell,$$

where i_t is the observed target rate and ε_t^ℓ denotes the residuals, which can be interpreted as monetary policy shocks. For all examples except Clarida et al. (1998), who explicitly state they use instrumental variables (IV), I use OLS as potential inconsistency of OLS estimates has been shown to be irrelevant for the estimation monetary policy rules in practice. In fact, OLS often yields a lower mean squared error (MSE) than IV regressions (Carvalho et al., 2021).

In contrast, the Taylor rule coefficients in the discrete case, $\alpha_{\mathcal{D}}$, are estimated using the

model

$$i_t = \mathcal{D}(X_t, \alpha_{\mathcal{D}}) + \varepsilon_t^{\mathcal{D}}.$$

OLS cannot be applied here as the model is non-linear. Thus, I estimate α_D on a grid and keep the parameter combination that minimizes the MSE.

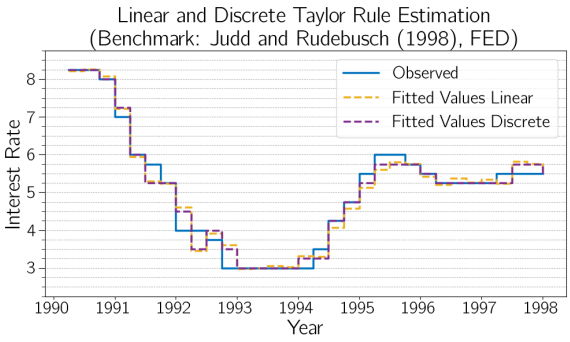
I do not use ordered probit or ordered logit—although these methods are commonly applied to discrete outcome variables—for two reasons. First, ordered models maximize the likelihood of observing the ordered categories in the sample rather than minimizing the MSE of the outcome variable. While this property is suitable for purely categorical variables without a cardinal interpretation, interest rates, even when discrete, are cardinal. Because ordered models do not necessarily minimize the MSE, the fit of discrete and linear rules would not be comparable if the discrete rule were estimated using ordered probit. Second, ordered probit and logit estimate the categorical thresholds along with the linear coefficients, which conflicts with the exogenous thresholds I impose when specifying the discrete rule (1) as an approximation to its linear counterpart. This approximation is also used for the monetary policy rule in the structural model presented in Section 3.

Again, $\varepsilon^{\mathcal{D}}$ can be interpreted as monetary policy shock, as it captures the surprise component of monetary policy. As $i_t \in I$, it follows that $\varepsilon_t^{\mathcal{D}} \in I$—that is, the shock itself is a multiple of 25 basis points. This feature is realistic and also reflected in the analysis by Chang and Schorfheide (2024), who specifically examine responses to a 25-basis-points monetary policy shock. In the structural model specified in the Section 3, I will distinguish between observed discrete, so-called "effective" monetary policy shocks and underlying continuous shock processes.

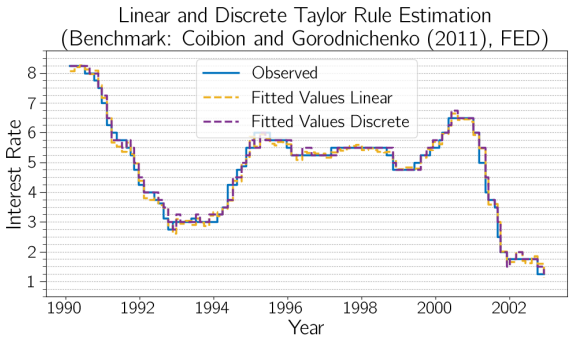
2.2 Results

The selection of benchmark specifications for estimating linear and discrete rules is based on two criteria. First, the target rate as the outcome variable must be discrete for the respective central bank and time period, which excludes earlier studies for some countries. Second, there needs to be sufficient variation of the target rate, which in practice restricts the sample to pre-2008 or post-2022 data. Table 1 lists the selected studies along with model fit statistics for the corresponding linear and discrete Taylor rules. As none of the included papers relies on data since 2022, I additionally estimate the best-fitting quarterly-frequency and the only monthly-frequency rule in the literature sample on U.S. market rate data for this recent time period.

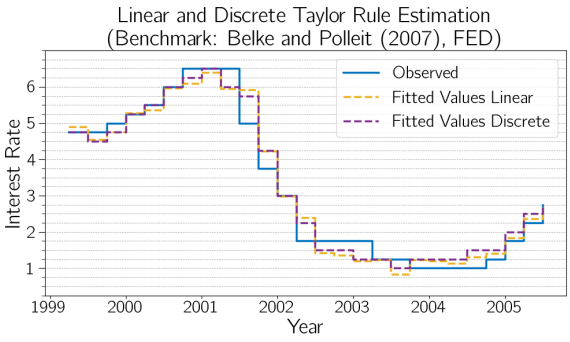
Details on the data underlying all estimation exercises are given in Appendix B.



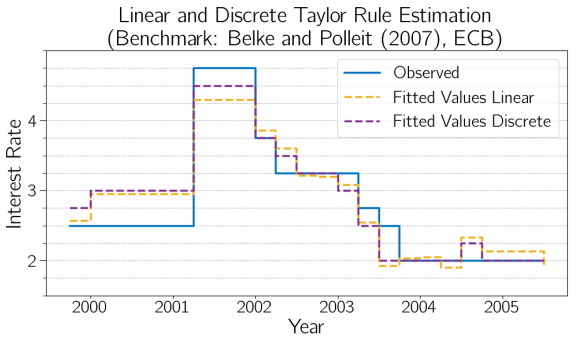
(a) FED, 1990.Q1–1997.Q4, policy rate.



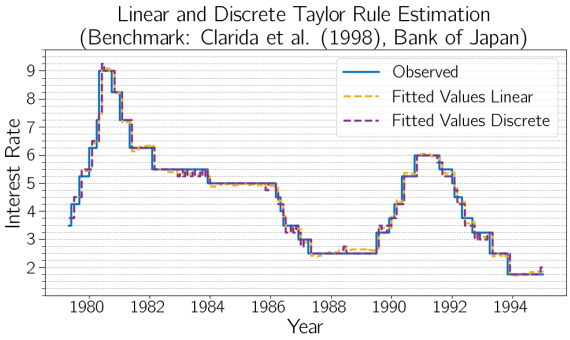
(b) FED, 1990–2002, policy rate.



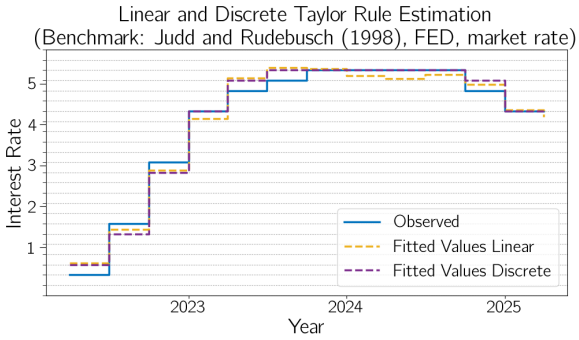
(c) FED, 1999.Q1–2005.Q2, policy rate.



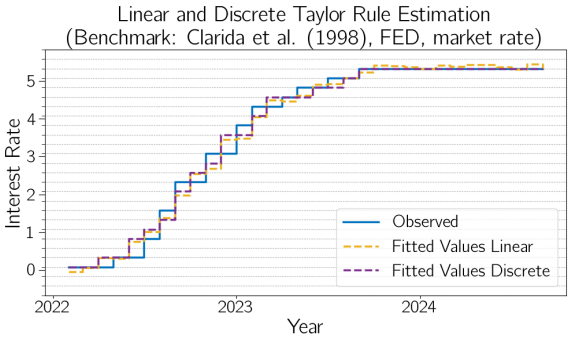
(d) ECB, 1999.Q1–2005.Q2, policy rate.



(e) Bank of Japan, 1979.M4–1994.M12, policy rate.



(f) FED, 2022.Q1–2025.Q2, market rate.



(g) FED, 2022.M1–2024.M8, market rate.

Figure 3: Fitted values for estimated linear and discrete Taylor rules.

Table 1: Model fit statistics for estimated linear and discrete Taylor rules based on examples from the literature.

Benchmark Specification	Area	Period	MSE		MAE		Zero-Residual Periods (Discrete, %)
			Linear	Discrete	Linear	Discrete	
Judd and Rudebusch (1998)	U.S.	1990.Q1–1997.Q4	0.0676	0.0508	0.1895	0.1406	56.25
Coibion and Gorodnichenko (2011)	U.S.	1990–2002[a]	0.0378	0.0355	0.1507	0.1178	56.73
Belke and Polleit (2007)	U.S.	1999.Q1–2005.Q2	0.1192	0.0986	0.2657	0.2404	30.77
Belke and Polleit (2007)	EA	1999.Q1–2005.Q2	0.0656	0.0515	0.1949	0.1471	52.94
Clarida et al. (1998)	JP	1979.M4–1994.M12	0.0735	0.0751	0.1685	0.1362	64.02
Post-2022 Estimates for Market Rate (EFFR):							
Judd and Rudebusch (1998)	U.S.	2022.Q1–2025.Q2	0.0372	0.0288	0.1717	0.1154	53.85
Clarida et al. (1998)	U.S.	2022.M1–2024.M8	0.0368	0.0371	0.1486	0.1172	59.38

[a] Each observation corresponds to one FOMC meeting date.

2.2.1 FED, 1990–1997 (Judd and Rudebusch, 1998)

First, I estimate a linear Taylor rule as specified by Judd and Rudebusch (1998) and its discrete counterpart. The estimated rule is given by

$$i_t = \beta_0 + \beta_1 i_{t-1} + \beta_2 i_{t-2} + \beta_3 \overline{\pi}_t + \beta_4 x_t + \beta_5 x_{t-1} + \varepsilon_t. \tag{2}$$

Here, $\overline{\pi}_t$ denotes average inflation across the last four quarters, and x_t denotes the quarterly output gap. The notation of parameters and variables differs from the original paper and has been adapted for consistency with subsequent specifications.

The rule is estimated using quarterly data. In the original paper, the estimation covers three separate time periods from 1970 to 1997, corresponding to the terms of three Federal Reserve chairmen. I restrict the analysis to the subperiod 1990.Q1–1997.Q4, which is a subset of the Greenspan term. This restriction is motivated by the fact that the FED target rate has been set on a 25-basis-points grid only since 1990. Prior to that, it was on a 6.25-point grid, mimicking a continuous rate given the substantial variation in interest rates before 1990.

I find that both the mean squared error (MSE) and mean absolute error (MAE) are significantly smaller when using the discrete rule. Specifically, the MSE decreases from 0.0676 to 0.0508, and the MAE from 0.1895 to 0.1406 (see Table 1). Note that the fitted interest rate is given in percentage points. Thus, a reduction of the MAE by about 0.05 means that the fitted values are on average 5 basis points closer to the observed interest rate with a discrete rule. Further, for more than 50% of all periods, the discrete-rule fitted values feature zero residuals (this measure corresponds to the hit ratio in a probit model). Intuitively, this means that in the linear-rule model, residuals in more than half of all periods can be entirely explained by the lack of discretization. Fitted values for both rules and the observed target rate are depicted in Figure 3a.

2.2.2 FED, 1990–2002 (Coibion and Gorodnichenko, 2011)

Second, I follow the approach by Coibion and Gorodnichenko (2011), who estimate

$$i_t = \beta_0 + \beta_1 i_{t-1} + \beta_2 i_{t-2} + (1 - \beta_1 - \beta_2)\left(\beta_3 \frac{\mathbb{E}_t \pi_{q1} + \mathbb{E}_t \pi_{q2}}{2} + \beta_4 \mathbb{E}_t g y_{qt} + \beta_5 \mathbb{E}_t x_{qt}\right) + \varepsilon_t$$

in their best-fitting specification. Their model is different from all other specifications as each observation corresponds to one FOMC meeting date, such that one period lasts approximately six weeks. Further, they use tealbook data—forecasts available to the FOMC in the given meeting—for output and inflation. Specifically, $\frac{\mathbb{E}_t \pi_{q1} + \mathbb{E}_t \pi_{q2}}{2}$ is average inflation expected over the next two quarters, $\mathbb{E}_t g y_{qt}$ expected output growth in the current quarter, and $\mathbb{E}_t x_{qt}$ the expected output gap in the current quarter. Again, I restrict the estimation period to years after 1990, ensuring that the target rate stays on a 25-basis-points grid in all periods.

The rule fits the data remarkably well, even in its linear specification, with an MSE of 0.0378 and an MAE of 0.1507. Again, the discrete rule features lower errors, with an MSE of 0.0355 and an MAE of 0.1178, which implies a reduction by more than a fifth compared to the linear rule. The discrete rule yields zero residuals for almost 57% of all time periods.

2.2.3 FED and ECB, 1999–2005 (Belke and Polleit, 2007)

Next, I adopt the estimation from Belke and Polleit (2007), who compare monetary policy at the FED and the ECB in the period 1999–2005. They estimate a rule of the form

$$i_t = \beta_0 + \beta_1 i_{t-1} + \beta_2 x_t + \beta_3 \pi_t + \varepsilon_t,$$

where inflation π_t denotes annual inflation, defined as inflation relative to the same quarter in the previous year. Like Judd and Rudebusch (1998), the authors use quarterly data for their main exercise.

For both the FED and the ECB, the estimates indicate a lower MAE and a lower MSE for the discrete Taylor rule. The improvement is significantly larger for the ECB, amounting to about a fifth of the linear-rule MSE and a quarter of the linear-rule MAE in this case. Accordingly, the discrete rule produces zero residuals during more than half of the observation period for the ECB, compared to 31% for the FED. Figures 3c (FED) and 3d (ECB) provide a graphical representation of these results.

2.2.4 Bank of Japan, 1979–1994 (Clarida et al., 1998)

Further, I adopt a Taylor rule specification from Clarida et al. (1998), given by

$$i_t = \beta_0 + \beta_1 i_{t-1} + \beta_2 \pi_{t+12} + \beta_3 x_t + \varepsilon_t. \tag{3}$$

Here, π_{t+12} denotes 12-month-ahead inflation relative to month t, making the rule forward-looking. The estimation is based on monthly data. For inflation and the output gap, instruments are used. Again, details are provided in Appendix B.

The authors estimate this rule for six countries in total. They find that monetary policy in three out of these six countries (in France, Italy, and the United Kingdom) was dominated by German monetary policy. The three remaining countries (Germany, Japan, and the United States) conducted an independent monetary policy, yet target rates in Germany and the U.S. deviated from the discrete grid for a substantial share of the sample period (as already discussed in the context of Judd and Rudebusch (1998)). Therefore, the estimation of a discrete rule is carried out for Japan only.

In contrast to the previous exercises, the MSE is slightly larger for the discrete rule than the linear rule (0.0751 vs. 0.0735). Nevertheless, the MAE remains more than 3 basis points smaller (0.1362 vs. 0.1685). The larger MSE arises because residuals are themselves bounded to a discrete grid, as discussed earlier. In this case, where both rules fit relatively well, deviations—if they occur at all—are relatively large for the discrete rule (see Figure 3e). Larger deviations are penalized more by the MSE than the MAE.

Note that the fit of the linear rule benefits considerably from the monthly frequency of the data. This is because the lagged target rate enters the estimated linear rule (3). When the data are monthly rather than quarterly, interest rate jumps occur in a smaller share of periods, resulting in a high estimated autocorrelation of the target rate ($\rho = 0.95$). Since the lagged target rate is discrete and a regressor, this enables the linear rule to closely track the discrete one. At the same time, the monthly frequency of the data yields a high share of periods for which the discrete rule yields zero residuals (64%)

2.2.5 FED, 2022–2025, Using the Judd and Rudebusch (1998) and Clarida et al. (1998) Specification

Finally, I assess the recent explanatory power of discrete rules by estimating the Judd and Rudebusch (1998) and Clarida et al. (1998) specifications (equations (2) and (3)) for the ongoing period following the end of the zero-lower-bound era in 2022. As before, the former is estimated on quarterly and the latter on monthly data. As outlined in Section 2.2.4, 12-period-ahead inflation is used as a regressor, which reduces the effective estimation period for the monthly exercise to 2022.M1–2024.M8. Recall that Clarida et al. (1998) estimated their rule not only for Japan but also for the U.S., which is why

I adopt their specification here.

For this time period, the estimation is now carried out for the effective federal funds rate as the overnight market rate that corresponds most closely to the target rate. Recall that the effective federal funds rate has been as discrete as the target rate in this time period. However, both rates differ by a constant, which makes it necessary to shift all points on the interest rate grid for the estimation (see Figure 2). As monthly or quarterly observations, the last available daily effective federal funds rates in each time period are used. The same approach was applied for the previous target-rate-based estimations. Computing the average market rate (or target rate) instead would yield observations that are not an element of the interest rate grid whenever the interest rate jumps to another grid point within a period.

Estimation results confirm the previous finding that the discrete version of each rule produces smaller mean absolute errors. For the Judd and Rudebusch (1998) specification and quarterly data, this reduction is larger than for the Clarida et al. (1998) benchmark and monthly data (0.1717 to 0.1154 vs. 0.1486 to 0.1172). The mean squared error decreases only for quarterly data (0.0372 to 0.0288). It is larger for monthly data, which is line with the result for the 1979–1994 period in Japan. Again, this difference is small (0.0371 vs. 0.0368). In both settings, the discrete-rule fitted values feature zero residuals for more than half of all time periods.

2.2.6 Summary

Overall, the estimates show that applying discrete Taylor rules can significantly reduce residuals. This holds across multiple central banks, time periods, and Taylor rule specifications. Mean absolute errors are up to 33% smaller on average and are equal to zero for up to 64% of all time periods when the discrete nature of target rates is taken into account. Similar findings emerge for post-2022 market rates in the U.S. Regarding the mean squared error, the linear rule performs slightly better particularly for monthly-frequency estimates, a result stemming from the large weight the MSE attributes to larger residuals. Intuitively, the advantage of discrete rules can be expected to diminish when the discrete rate step size is reduced. This intuition is confirmed based on Taylor (1993) for the pre-1990 period in Appendix C. Before 1990, policy rates in the U.S. were set in 6.25-basis-points increments.

Motivated by the empirical performance of discrete interest rate rules, I specify a New-Keynesian structural model incorporating this feature in the next section.

3 Structural Model

3.1 Basic Setup

I study a simple log-linearized three-equation New-Keynesian model in discrete time. The model is an adapted version of the model by Galí (2015). The formal derivation is provided in Appendix D. The IS and Phillips curve are given by

$$x_t = \mathbb{E}_t x_{t+\Delta} - \frac{\Delta}{\sigma}\mathbb{E}_t\left(i_{t+\Delta} - \tilde{\pi}_{t+\Delta} - \bar{i}\right) + \lambda_z z_t - \lambda_a a_t, \tag{4}$$

$$\tilde{\pi}_t = \left(\frac{\beta}{1+\pi}\right)^{\Delta} \mathbb{E}_t \tilde{\pi}_{t+\Delta} + \kappa x_t. \tag{5}$$

Here, x_t denotes the output gap, $\tilde{\pi}_t$ stationarized inflation, i_t the nominal interest rate, z_t a demand shock, and a_t a total factor productivity (TFP) shock. σ is the inverse of the intertemporal elasticity of substitution, and $\bar{i} = \rho + \pi$ the steady-state nominal interest rate as the sum of the time preference rate (or natural real rate) ρ and the inflation target π. Thus, $\tilde{\pi}_t = \pi_t - \pi$, where π_t denotes non-stationarized inflation. λ_z, λ_a, and κ are composite parameters derived in Appendix D.

The period length Δ is given in terms of years (e.g., if $\Delta = \frac{1}{365}$, as implemented later, a period spans one day). The same applies to the parameters $\bar{i}$, π, and ρ. Accordingly, inflation and the interest rate are annualized. In steady state, z_t, a_t, x_t, $x_{t+\Delta}$, $\tilde{\pi}_t$, and $\pi_{t+\Delta}$ are zero, and $i_{t+\Delta} = \bar{i}$.

There are three differences relative to the original model by Galí (2015). First, the period length is set to Δ rather than one. Second, the inflation target π is allowed to differ from zero, and $\tilde{\pi}_t$ denotes the stationarized inflation rate. Finally, the expected nominal interest rate in period $t + \Delta$, instead of period t, enters the IS curve (4). This implies that households expect bonds purchased in period t to yield interest $\mathbb{E}_t\left(1 + i_{t+\Delta}\right)$ instead of $(1 + i_t)$ when maturing in period $t + \Delta$. This assumption ensures that the model can be solved given the discrete interest rate rule introduced below. To micro-found the index shift, one needs to specify the household budget constraint as done in (18). There, I assume that a bond purchased in period $t - \Delta$ and maturing in period t yields interest $(1 + i_t)^{\Delta}$ instead of $(1 + i_{t-\Delta})^{\Delta}$. This assumption seems reasonable particularly for floating-rate bonds with time-variant interest rates. Even for fixed-rate bonds, it is realistic given that the period length Δ will be calibrated to one day throughout the remainder. In this case, it reflects that the execution of bond-purchase orders may take a day. Quantitatively, the time-index shift has no significant effect on the model's dynamics, as shown in Appendix E.1.

The model is closed by a Taylor rule determining the nominal rate i_t. In case of a linear

Taylor rule, it is given by the function $\ell(\tilde{\pi}_t, x_t, v_t)$, defined as

$$i_t = \ell(\tilde{\pi}_t, x_t, v_t) = \bar{i} + \phi_\pi \tilde{\pi}_t + \phi_x x_t + v_t, \tag{6}$$

where v_t denotes a monetary policy shock, and ϕ_π and ϕ_x are parameters quantifying the interest rate's response to deviations of inflation and the output gap from their steady-state values.
All shocks follow AR(1) processes, driven by innovations ε_t^i for $i \in \{z, a, v\}$:

$$z_t = \rho_z^\Delta z_{t-\Delta} + \varepsilon_t^z \tag{7}$$
$$a_t = \rho_a^\Delta a_{t-\Delta} + \varepsilon_t^a \tag{8}$$
$$v_t = \rho_v^\Delta v_{t-\Delta} + \varepsilon_t^v, \tag{9}$$

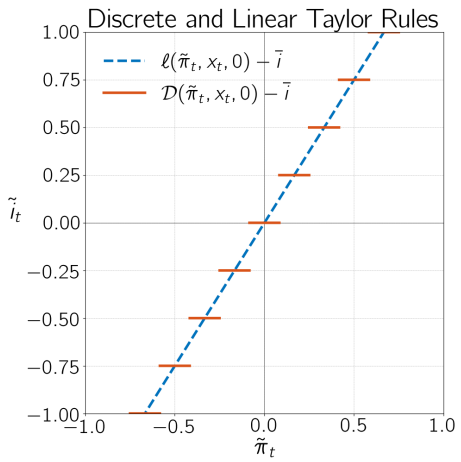
where ρ_i denotes the annual persistence of shock i, and the exponent Δ adjusts for the period length.

3.2 Adding Discrete Monetary Policy

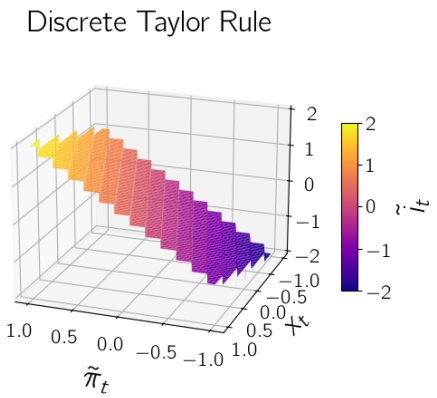
As described in the introduction, a linear Taylor rule as given in (6) that holds in every period does not align with observed data. On the one hand, realized policy rates are typically set in increments of 25 basis points, a feature that the linear rule does not capture. On the other hand, infrequent monetary policy decisions at discrete points in time imply that the interest rate equals its own lag all other periods.
These gaps to reality can be bridged by adding two modifications to the model. First, as in Section 2, define a set $I = \{\dots, -2i^{\text{step}}, -i^{\text{step}}, 0, i^{\text{step}}, 2i^{\text{step}}, \dots\}$, which contains all multiples of i^{step}. Define $\mathcal{D}(\tilde{\pi}_t, x_t, v_t)$ as a discrete function which approximates the linear Taylor rule (6), subject to the nominal rate belonging to set I:

$$\mathcal{D}(\tilde{\pi}_t, x_t, v_t) = \arg\min_{i_t \in I} \left(i_t - \ell(\tilde{\pi}_t, x_t, v_t)\right)^2. \tag{10}$$

I illustrate the relation between the linear Taylor rule $\ell(\tilde{\pi}_t, x_t, v_t)$ and its discrete approximation $\mathcal{D}(\tilde{\pi}_t, x_t, v_t)$ in Figure 4a for a toy calibration. For this and subsequent figures, it is convenient to define $\tilde{i} = i_t - \bar{i}$ as the deviation of the nominal interest rate from the steady-state nominal rate.
The second feature which I add to the model to come closer to the data is infrequent opportunities for interest rate adjustments. As outlined in the introduction, most central banks adjust their target rate or range only at predefined dates that are more or less evenly spaced throughout the year.
For the remainder of this paper, assume that $t = 0$ is the initial period in the model. Let μ_1 denote the time between two monetary policy decisions in terms of years. For



(a) Deviation of the nominal interest rate from its natural level when set following a discrete Taylor rule $\mathcal{D}(\tilde{\pi}_t, x_t, v_t)$ or a linear Taylor rule $\ell(\tilde{\pi}_t, x_t, v_t)$, across different levels of inflation, assuming $x_t = 0$.



(b) Deviation of the nominal interest rate from its natural level when set according to a discrete Taylor rule $\mathcal{D}(\tilde{\pi}_t, x_t, v_t)$, across different levels of inflation and the output gap.

Figure 4: Discrete and linear Taylor rules. Calibration: $\bar{i} = 6$, $\phi_\pi = 1.5$, $\phi_x = 0.5$.

example, if a central bank meets eight times per year, such as the FED or the ECB, then $\mu_1 = \frac{1}{8}$. Let μ_2 denote the time in years between period 0 and the first central bank decision (with $\mu_2 \leq \mu_1$). Then, the set M comprises all time periods in which the central bank meets and is free to adjust the policy rate:

$$M = \left\{ \Delta \times \left\lfloor \frac{\mu_1 n + \mu_2}{\Delta} \right\rfloor \middle| n \in \mathbb{N} \right\}. \tag{11}$$

Here, $\mathbb{N}$ denotes the set of all natural numbers excluding zero. Periods in which the central bank may reset the interest rate are indexed as $t_m \in M$. The first period after period t_m in which a central bank meets is denoted as t_{m+1}. The first meeting period in the entire time horizon is denoted as t_0.

Denote m_t^+ as the future meeting period closest to period t, i.e., the minimum element of set M that is strictly larger than t. Likewise, denote m_t^- as the maximum element of M that is weakly smaller than t, i.e., the period of the last meeting from the perspective of period t. To ensure the model can be solved, it is required that the Taylor rule is forward-looking. Specifically, I impose that it uses as inputs the expected values of output and inflation in period $m_t^+ - \Delta$, i.e., the last period before the next central bank decision. I discuss why this kind of forward-looking rule is convenient and show that it does not significantly affect results in Appendix E.

Then, the nominal interest rate i_t in any period t is given as

$$i_t = \begin{cases} \mathcal{D}\left(\mathbb{E}_t \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_t x_{m_t^+ - \Delta}, v_t\right) & \text{if } t \in M, \\ i_{t-\Delta} & \text{otherwise.} \end{cases} \tag{12}$$

In a linear-rule model with continuously updated interest rates, residuals between realized rates i_t and the interest rate rule evaluated for a zero monetary policy shock are equal to the monetary policy shock itself, i.e., $\ell(\tilde{\pi}_t, x_t, v_t) - \ell(\tilde{\pi}_t, x_t, 0) = v_t \; \forall \; t$. This property does not hold in the discrete model, both due to discrete rates and infrequent meetings. Instead, one may define this difference as an *effective* monetary policy shock $\tilde{v}_t$. Formally,

$$\tilde{v}_t = \begin{cases} \mathcal{D}\left(\tilde{\pi}_{m_t^+ - \Delta}, x_{m_t^+ - \Delta}, v_t\right) - \mathcal{D}\left(\tilde{\pi}_{m_t^+ - \Delta}, x_{m_t^+ - \Delta}, 0\right) & \text{if } t \in M, \\ \tilde{v}_{t-\Delta} & \text{else.} \end{cases} \tag{13}$$

This is the effective disturbance observed by agents, and it corresponds to the residuals estimated for discrete rules in Section 2 (where all periods where considered meeting periods implicitly). Note that it always is a multiple of i^{step} itself. In contrast, v_t may be interpreted as a continuous, underlying preference shock in the central bank's decision committee that may or may not be sufficiently large to shift the target rate to another grid point in a meeting period. The relation between v_t and $\tilde{v}_t$ is examined for a simulated business cycle in Section 5.3.

3.3 Model Solution

Combining the IS curve, the Phillips curve, and monetary policy, the full model can be described as

$$\begin{aligned} x_t &= \mathbb{E}_t x_{t+\Delta} - \frac{\Delta}{\sigma} \mathbb{E}_t \left(i_{t+\Delta} - \tilde{\pi}_{t+\Delta} - \bar{i}\right) + \lambda_z z_t - \lambda_a a_t, \\ \tilde{\pi}_t &= \left(\frac{\beta}{1+\pi}\right)^{\Delta} \mathbb{E}_t \tilde{\pi}_{t+\Delta} + \kappa x_t, \\ i_t &= \begin{cases} \mathcal{D}\left(\mathbb{E}_t \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_t x_{m_t^+ - \Delta}, v_t\right) & \text{if } t \in M, \\ i_{t-\Delta} & \text{otherwise.} \end{cases} \end{aligned} \tag{14}$$

It can be solved backward for $t = 0, \Delta, 2\Delta, \ldots, T$ given a terminal condition for $\mathbb{E}_{T-\Delta} x_T$, $\mathbb{E}_{T-\Delta} \tilde{\pi}_T$, exogenous shocks ε_t^z, ε_t^a, and ε_t^v, and an initial interest rate i_0 if $0 \notin M$ (i.e., if there is no central bank meeting in the first period at which an initial interest rate could be determined).

It is convenient to start the derivation of the backward solution by considering period $m_t^+ - \Delta$, i.e., the last period before a central bank meeting. Assuming that the previous

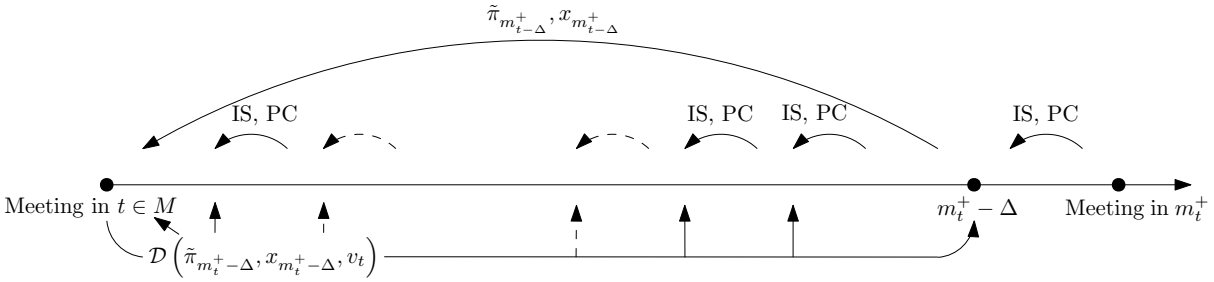


Figure 5: Backward solution approach for the structural model given in (14), exemplified for an interval between two central bank meetings.

central bank meeting was in period t, the model equations read as

$$
\begin{aligned}
x_{m_t^+-\Delta} &= x_{m_t^+} - \frac{\Delta}{\sigma}\left(i_{m_t^+} - \tilde{\pi}_{m_t^+} - \bar{i}\right) + \lambda_z z_{m_t^+-\Delta} - \lambda_a a_{m_t^+-\Delta}, \\
\tilde{\pi}_{m_t^+-\Delta} &= \left(\frac{\beta}{1+\pi}\right)^{\Delta} \tilde{\pi}_{m_t^+} + \kappa x_{m_t^+-\Delta}, \\
i_{m_t^+-\Delta} &= i_{m_t^+-2\Delta} = \mathcal{D}\left(\tilde{\pi}_{m_t^+-\Delta}, x_{m_t^+-\Delta}, v_t\right).
\end{aligned}
$$

Here, I drop expectations operators for simplicity. Observe that $x_{m_t^+-\Delta}$ as given by the IS curve depends on exogenous shocks and future variables only and is therefore known when solving backward. Using $x_{m_t^+-\Delta}$ in the Phillips curve yields $\tilde{\pi}_{m_t^+-\Delta}$. As the Taylor rule evaluated in the period of the last central bank meeting, t, was forward-looking and dependent on $\tilde{\pi}_{m_t^+-\Delta}$, $x_{m_t^+-\Delta}$ and the exogenous shock v_t. Thus, one can now compute the interest rate for periods $t, \dots m_t^+ - \Delta$. Finally, iterating on the IS and Phillips curve yields the output gap and inflation for all periods between the two meetings. In the period before the previous meeting, $t - \Delta$, the procedure can be repeated to solve for all variables in the previous meeting interval. Note that the solution is unique given the terminal condition. A graphical description of the backward solution method is provided in Figure 5.

Additional assumptions need to be made only where central bank decision intervals are incomplete. At the beginning of the time horizon, the initial interest rate i_0 must be calibrated if there is no central bank meeting in period 0. This interest rate is imposed for $k = 0, \dots, t_0$ (recall that t_0 indexes the time period of the first central bank meeting). A necessary condition for $t_0 > 0$ is $\mu_2 > 0$. In such a setting, monetary policy cannot immediately react to shocks hitting in period 0, as studied in Section 4.[1]

[1] A further assumption without an effect on any of the results presented in the remainder of this paper may need to be made at the end of the time horizon $t = 0, \Delta, 2\Delta, \dots, T$. Specifically, there are indeterminate interest rates whenever $m_T - \Delta > T$, i.e., whenever the next central bank meeting after the end of the time horizon would not take place in period $T + \Delta$. Intuitively, this means that the forward-looking Taylor rule lacks observations of the output gap and inflation for the time period it is supposed to refer to. In this case, I only solve the model for $t = 0, \dots, t_{\overline{m}} - \Delta$, where $t_{\overline{m}}$ denotes the maximum element of M that is weakly smaller than T. For all later periods, I impose the terminal condition.

As terminal conditions, I set $\mathbb{E}_{T-\Delta} x_T = 0$, $\mathbb{E}_{T-\Delta} \tilde{\pi}_T = 0$, corresponding to the steady state of a model with a linear Taylor rule. I assume $\bar{i} \in I$. Therefore, the steady-state nominal rate is a multiple of 25 basis points and can be set by the monetary authority, such that the steady state can be attained. This assumption is reflected in Figure 4. Note that the monetary policy response is inactive around steady state and, in general, for any fluctuation of the output gap and inflation that is not large enough to let the interest jump to another element in I. Furthermore, it is inactive in any period without a central bank meeting. Potential indeterminacy arising from this is not studied further in this paper. Effectively, the terminal condition and the backward solution serve as an equilibrium selection rule.

In principle, the model could also be solved forward, given an initial condition for x_0, $\tilde{\pi}_0$, and i_0. However, the forward solution does not necessarily exist or may not be unique. For a derivation and discussion, see Appendix F.

3.4 Calibration

After deriving the model solution, I now present the calibration of model parameters shown in Table 2. The parameters fall into three distinct groups.

First, the model includes parameters from the benchmark specification of Galí (2015). For these, the original calibration is adopted. Except for the Taylor rule parameters ϕ_π and ϕ_x, all parameters in this group are parameters related to household preferences, technology, or assumptions about exogenous processes.

Second, the table lists five parameters absent from Galí (2015): the period length Δ, the central bank's inflation target and steady-state inflation π, and parameters that describe the discreteness and infrequency of monetary policy, namely i^{step}, μ_1, and μ_2. Δ is calibrated to $\frac{1}{365}$. As all parameters and variables are annualized, this implies that one period corresponds to one day. i^{step} is set to 0.25 percentage points, reflecting rate adjustments in 25-basis-point increments. μ_1 equals $\frac{1}{8}$, corresponding to two interest rate adjustments per quarter, as typically observed for the FED and the ECB. μ_2 is set to either 0 or $\frac{1}{8}$, depending on the scenario studied. Steady-state inflation π is set to 2.00. Together with $\rho = 4.00$, following Galí (2015), this implies $\bar{i} = 6.00$, which is a multiple of 0.25 and can be set by the central bank as the nominal rate. Therefore, the steady state can be attained.

Finally, the log-linearized model equations (14) involve four composite parameters derived in Appendix D. Their calibration follows directly from the calibration of their components. Because these composite parameters depend on the period length Δ, their values differ from those in Galí (2015) since $\Delta \neq 1$.

Table 2: Calibration of model parameters. All parameters appearing in Galí (2015) are calibrated according to this source. Composite parameters are derived in Appendix D.

Notation	**Definition/Formula**	**Calibration**
σ	Inverse of the elasticity of intert. subst.	1.00
ρ	Discount rate (in percent)	4.00
φ	Frisch elasticity of labor supply	5.00
ϵ	Elasticity of substitution between goods	9.00
θ	Price stickiness	0.75
α	Capital share	0.25
ρ_z	Persistence demand shock	0.50
ρ_a	Persistence supply shock	0.50
ρ_v	Persistence monetary shock	0.50
ϕ_π	Linear Taylor rule response to inflation	1.50
ϕ_x	Linear Taylor rule response to output gap	0.50
	Parameters inexistent in Galí (2015):	
π	Inflation target (in percent)	2.125
Δ	Period length	$\frac{1}{365}$
i^{step}	Interest rate step size (in percent)	0.25
μ_1	Gap between central bank decisions	$\frac{1}{8}$
μ_2	Gap between $t=0$ and first central bank decision	$\frac{1}{8}$
	Composite parameters:	
β	$\frac{1}{1+\rho/100}$	0.9615
λ_a	$\frac{(1+\varphi)\left(1-\rho_a^\Delta\right)}{\sigma(1-\alpha)+\varphi+\alpha}$	0.0019
λ_z	$\frac{1-\rho_z^\Delta}{\sigma}$	0.0019
κ	$\frac{1-\theta^\Delta}{\theta^\Delta}\frac{1-\left(\frac{\beta\theta}{1+\pi/100}\right)^\Delta}{\Delta}\frac{1-\alpha}{1-\alpha+\alpha\varepsilon}\left(\sigma+\frac{\varphi+\alpha}{1-\alpha}\right)$	0.0023

4 New Patterns for the Response to MIT Shocks

In the following, I study the responses of the model economy to demand, supply, and monetary policy shocks. I examine the extent to which these responses are driven by the discrete interest rate grid and infrequent central bank meetings by carrying out a decomposition. Finally, I demonstrate that in a discrete setting, the responses of model variables are inhomogeneous with respect to the shock size.

4.1 Impulse Response Functions for the Discrete-Rule Model and Counterfactuals

As a preliminary step for the subsequent decomposition, I first compare three monetary policy regimes. As an example, consider a period-0 demand shock ε_0^z of size one. Impulse responses for the three regimes are presented in Figure 6.

The first scenario corresponds to a model in which the interest rate follows the standard linear Taylor rule (6) and is adjusted every period. However, I replace the rule's input arguments output gap and inflation by their expected future values in period $t + \Delta \times \lfloor \mu_1/\Delta \rfloor - \Delta$. Following (11), this means that the linear rule in this setting is as forward-looking in every period as the discrete rule in the full model (14) is in a meeting period, which ensures comparability. All variables in this scenario are assigned the superscript "systematic", as they will correspond to the systematic component in the later decomposition. In summary,

$$i_t^{\text{systematic}} = \ell\left(\mathbb{E}_t \tilde{\pi}^{\text{systematic}}_{t+\Delta\times\lfloor\mu_1/\Delta\rfloor-\Delta}, \mathbb{E}_t x^{\text{systematic}}_{t+\Delta\times\lfloor\mu_1/\Delta\rfloor-\Delta}, v_t\right). \tag{15}$$

With the forward-looking nature being the only modification compared to the textbook model, the resulting impulse response functions for output, inflation, and the interest rate provided in Panel 6a look standard. The effect of the shock decays smoothly, and all variables return to their steady-state values in finite time.

In the setting studied in Panel 6b, the central bank may still set any real number as the interest rate, yet it is now restricted to infrequent meetings. Variables in this counterfactual are denoted by the superscript "infrequency". Formally,

$$i_t^{\text{infrequency}} = \begin{cases} \ell\left(\mathbb{E}_t \tilde{\pi}^{\text{infrequency}}_{m_t^+-\Delta}, \mathbb{E}_t x^{\text{infrequency}}_{m_t^+-\Delta}, v_t\right) & \text{if} \quad t \in M, \\ i^{\text{infrequency}}_{t-\Delta} & \text{otherwise.} \end{cases} \tag{16}$$

As reported in Table 2, I impose $\mu_2 = \mu_1$. Given the definition of the set of meeting periods M (11), this calibration reflects the "worst-case" scenario in which the monetary authority is forced to wait for an entire meeting interval before being able to react to a shock materializing in period 0. Accordingly, the interest rate remains at its steady-state



(a) Linear Taylor rule, continuous interest rate adjustments ("systematic" model).

(b) Linear Taylor rule, infrequent interest rate adjustments ("infrequency" model).

(c) Discrete Taylor rule, infrequent interest rate adjustments (full model).

Figure 6: Impulse responses to a demand shock of size 1 for three monetary policy regimes.

level for the first six weeks, jumps in the first meeting period, and drops slightly on each subsequent meeting date, approximately mimicking the smooth decay observed in the model without infrequency. The initial non-responsiveness of the interest rate translates into the period-0 reaction of the output gap, which is approximately 0.1 percentage points larger than in the previous model. However, it starts mimicking the path corresponding to continuous rate adjustments when the central bank meets for the first time, and the inflation response remains almost unchanged during the entire time horizon. This outcome can be explained by agents' rational expectations: even when the interest rate is far off initially, the central bank's reaction after its first meeting is anticipated. This relatively low relevance of short-term interest rate movements for the output gap and inflation is a standard feature in forward-looking models (Woodford, 2003).

Finally, Panel 6c is based on the full model with discrete interest rate steps and infrequent adjustments as specified in (14). In this scenario, the interest rate response is absent before the first central bank meeting period, as already observed in the "infrequency" setting. After that, the rate jumps up to the next grid point, such that $\tilde{i}_t = 0.25$. It stays on this level for more than three years, interrupted only by two short-lived deviations to $\tilde{i}_t = 0.00$ that are observed from the third year of the time horizon onward. Eventually, the interest rate returns to its steady-state level. Compared to the previous linear-rule scenarios, monetary policy is therefore less active in the short and the long run but more active in the medium run.

This pattern has a substantial effect on the output gap. Driven by the expected relatively contractionary interest rate policy in the medium run, its initial decline is quicker than in the previous settings. However, the anticipated return of the interest rate to its steady-state level after three-and-a-half years entails an increase of the output gap between years 2 and 3.5. This trend is interrupted only by the two previously described temporary

interest rate reductions, which let the output gap path appear kinky. Finally, the output gap slowly returns to zero as the shock decays, even given an inactive monetary policy. This is ensured by the expectation of the steady state in the long run, as imposed by the terminal condition.

While the inflation response is less convex in the medium term, driven by the expectation of a looser monetary policy in the long run, it is far smoother than the output gap response in general. This difference between inflation and the output gap can be explained based on the IS and the Phillips curve (14). While the interest rate enters the IS curve directly, exerting a direct effect on the contemporaneous output gap, the Phillips curve is only indirectly affected.

The distinction of three counterfactual models is the basis for the following decomposition, which allows to illustrate and quantify the effect of discreteness and infrequency explicitly.

4.2 Decomposition

Computing differences in the paths for all variables across the three scenarios presented in Figure 6—the "systematic" model with a linear interest rate rule applied every period, the "infrequency" model with a linear Taylor rule but infrequent rate adjustments, and the full discrete model—allows quantifying the individual effects of each constraint on monetary policy.

First, the systematic component quantifies to which extent dynamics are still driven by the linear-rule model with continuous rate adjustments. For all variables, it is computed by solving the model given the interest rate rule (15).

Second, the infrequency component is the difference between a variable's path in the infrequency model with monetary policy following (16) and its path in the systematic model. Thus, it isolates the effect of infrequent meetings.

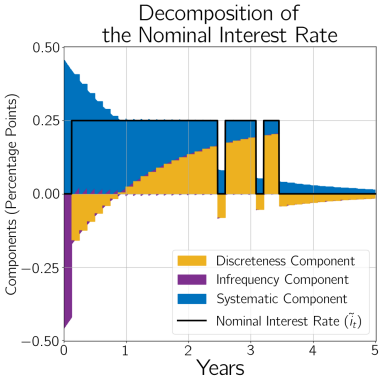
Third, the discreteness component equals the residuals between paths in the full model (14) and the infrequency model, thereby measuring the additional effect of discreteness.

Note that, for any variable, the sum of all components equals its path in the full, discrete-rule model. For instance, for the interest rate:

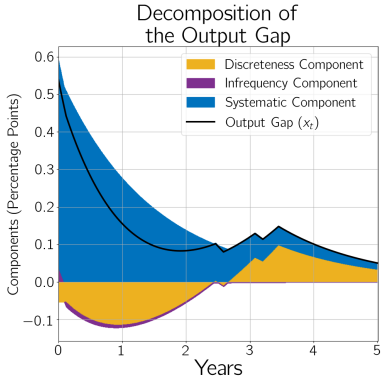
$$i_t = \underbrace{i_t^{\text{systematic}}}_{\text{systematic component}} + \underbrace{i_t^{\text{infrequency}} - i_t^{\text{systematic}}}_{\text{infrequency component}} + \underbrace{i_t - i_t^{\text{infrequency}}}_{\text{discreteness component}}$$

Decomposition results are presented in Figure 7 for demand, supply, and monetary policy shocks.

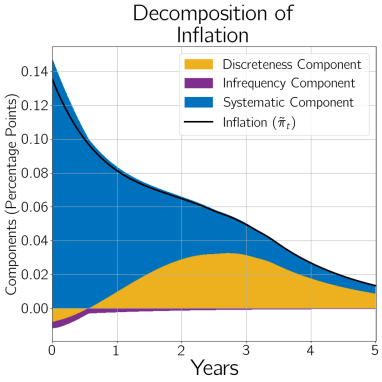
Across all shocks, the systematic component determines the sign of the response in any time period and for all variables. However, the discreteness component has a sizable effect on the interest rate. It first reduces its response to any kind of shock, then amplifies it in the medium term, and reduces it again in the long term, when the interest rate is set



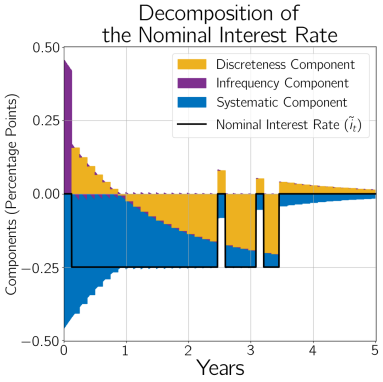
(a) Demand shock: nominal interest rate.



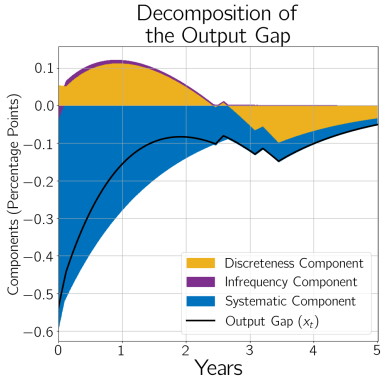
(b) Demand shock: output gap.



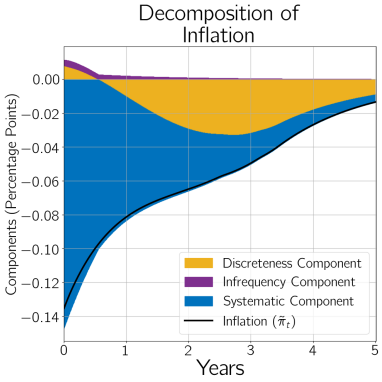
(c) Demand shock: inflation.



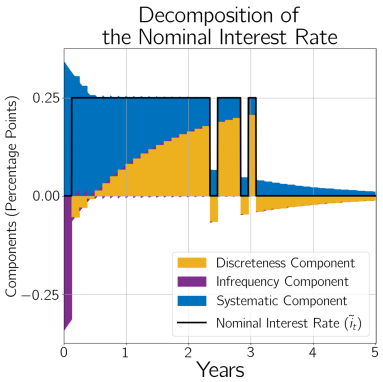
(d) Supply shock: nominal interest rate.



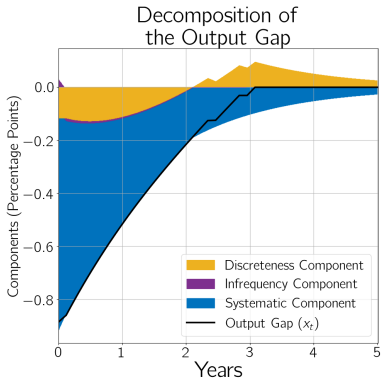
(e) Supply shock: output gap.



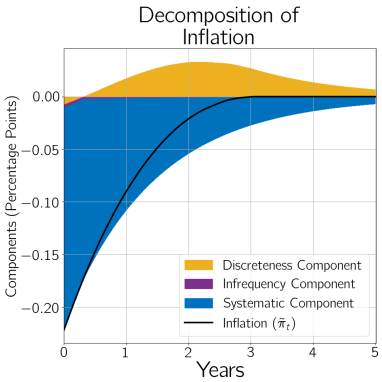
(f) Supply shock: inflation.



(g) Monetary policy shock: nominal interest rate.



(h) Monetary policy shock: output gap.



(i) Monetary policy shock: inflation.

Figure 7: Decompositions of impulse responses for demand, supply, and monetary policy shocks of size 1 in the discrete New-Keynesian model.

to its steady-state level in the discrete model but not in the linear counterfactual.
This pattern has a substantial effect on the output gap and inflation. However, as the model is forward-looking, only the amplifying medium-run and the alleviating long-run effect of discreteness on the interest rate response matter for these variables, making the output gap and inflation discreteness component switch signs exactly once. For a demand (supply) shock, this entails a U-shaped (hump-shaped) overall response for the output gap in the first three-and-a-half years, followed by a decay to steady state which is prolonged due to discreteness. For inflation, the effect is significant, too, leading to an approximately linear instead of geometric decay after the first year. The impact of discreteness over time reverses for a monetary policy shock: Discreteness amplifies deviations of the output gap and inflation from steady state in the short run and dampens them in the medium and long run, such that both variables are zero again after three years only.
Note that the sign and magnitude of the discreteness component also depend on the shock size and its interaction with the interest rate grid, as analyzed below in Section 4.3. Thus, universally valid statements about the sign of the discreteness component in the first or any other period cannot be derived from this exercise. However, it holds in general that the discreteness component has a substantial effect on all variables, and that the timing of this effect differs between the output gap and inflation. Further, the decomposition reveals that any kinks in the output gap path can be traced back to the discreteness component. Quantitative results on how discreteness matters during the business cycle are presented in Section 5, departing from the simplified analysis of MIT shocks.
In contrast to discreteness, infrequency appears to matter far less. Even for the interest rate, it is large only initially, when the interest rate reaction in a model without infrequency would be most pronounced but the interest rate is fixed at the steady-state level before the first central bank meeting. This inertia contributes positively to the initial deviation of the output gap from steady state for demand and supply shocks, whereas it dampens the initial output gap response for a monetary policy shock. However, these contributions are tiny compared to the initial effect on the interest rate. After the first central bank meeting, the sign of the infrequency component reverts, such that it alleviates the response of the output gap to demand and supply shocks and marginally amplifies its response to a monetary policy shock. This effect arises as infrequent interest rate setting (16) constitutes a marginally more active monetary policy than observed in the "systematic" model with the interest rate rule (15) being evaluated every period. The reason is that both monetary policy rules are equivalent in a meeting period, given the same levels of the future output gap and inflation. In the subsequent periods before the next meeting, however, the interest rate set in the infrequent model will remain at the same level, while the interest rate in the systematic model is continuously reduced given decaying shocks. This implies a relatively more active monetary policy in the infrequent model.

4.3 Inhomogeneity of Responses with Respect to the Shock Size

In contrast to the log-linearized New-Keynesian model with a linear Taylor rule, impulse responses do not scale linearly in the size of a given shock. This property stems from the fact that the interest rate step size $i^{\text{step}} = 0.25$ does not scale in the shock size, such that the discreteness component's effect is smaller for larger shocks, as exemplified in Figure 8 for a demand shock. Conversely, the relative size of the infrequency component is independent of the shock size, as it does not interact with the interest rate grid.

5 Business Cycle Analysis

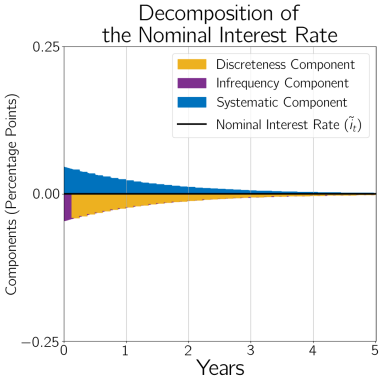
The previous section showed how difficult it is to draw straightforward conclusions about the effects of discreteness and infrequency on the economy based on the analysis of MIT shocks only. In addition to the inhomogeneity of components with respect to the shock size, the impact of discreteness and infrequency depends on the shock type, since it differs substantially between monetary policy shocks on the one hand and demand and supply shocks on the other hand. Finally, note that the initial sign and magnitude of the infrequency component was derived for a setting in which the interest rate is set to its steady-state level in period 0—an assumption that will often not hold in reality. To overcome these limitations and to quantify each component's contribution in a dynamic environment, I simulate and analyze a business cycle in this section.

To carry out the business cycle analysis, I first estimate the parameters underlying the demand and monetary policy shock processes for a completely linear version of my model and on U.S. data for the time period from 1966 to 2004, which corresponds to the period analyzed in Smets and Wouters (2007). The supply shock is directly observed for this period (Fernald, 2014), and its persistence and standard deviation are estimated separately.

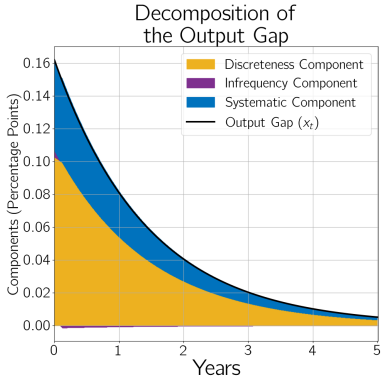
Note that the effective federal funds rate as the overnight market rate is used in this estimation exercise. As it was not yet discrete in the 1966–2004 period and fluctuated even between FOMC meetings, this allows identifying all parameters without explicitly accounting for discreteness and infrequency in the estimation procedure (see Figure 2). The estimated parameters are used to generate shock processes for $100,000$ periods, under which the discrete model is then simulated. Finally, the contributions of all components are analyzed graphically and quantitatively by decomposing each variable's variance.

5.1 Estimation of Shock Parameters

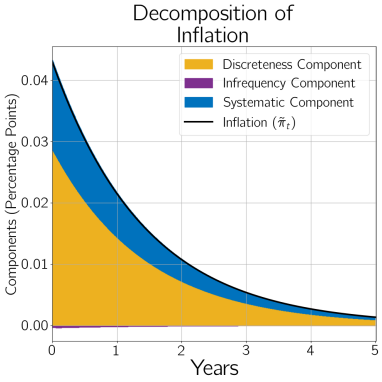
Standard deviations and the persistence of the demand and monetary policy shock processes are estimated for a quarterly-frequency version of the model in which a linear Taylor rule is applied in every period. For the supply shock, estimating an AR(1) process



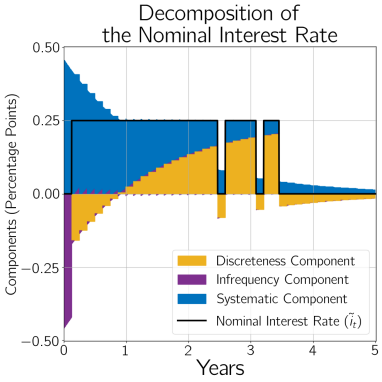
(a) Shock size 0.1, interest rate.



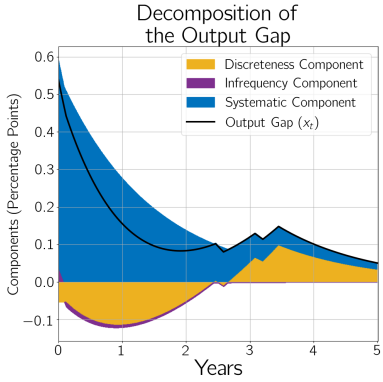
(b) Shock size 0.1, output gap.



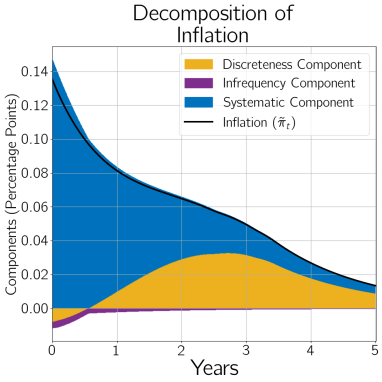
(c) Shock size 0.1, inflation.



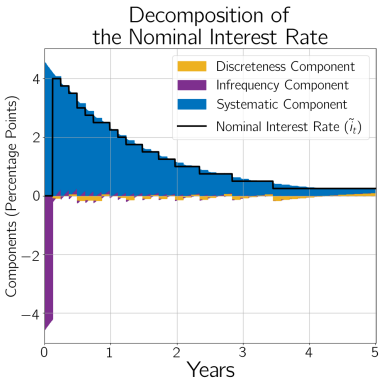
(d) Shock size 1.0, interest rate.



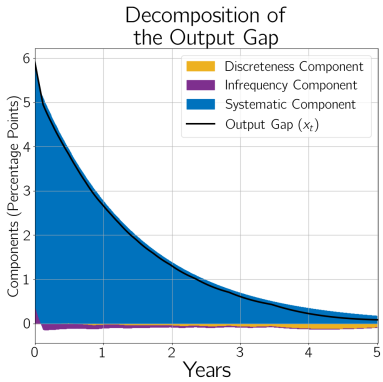
(e) Shock size 1.0, output gap.



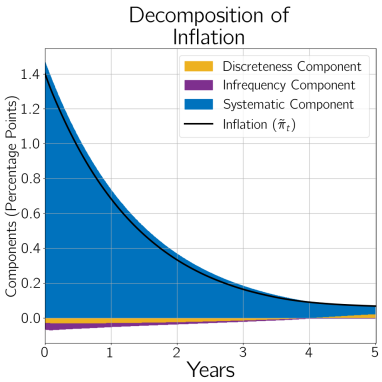
(f) Shock size 1.0, inflation.



(g) Shock size 10.0, interest rate.



(h) Shock size 10.0, output gap.



(i) Shock size 10.0, inflation.

Figure 8: Inhomogeneous impulse response functions for demand shocks of sizes 0.1, 1.0, and 10.0 in the discrete New-Keynesian model.

Table 3: Estimation results for quarterly shock persistence parameters and standard deviations.

	Prior			Posterior	
	Distr.	Mean	Stdev	Mean	Stdev
σ_z^q	invg	0.100	2.0000	1.827	0.3779
σ_v^q	invg	0.100	2.0000	0.534	0.0305
ρ_z^q	beta	0.500	0.2000	0.937	0.0164
ρ_v^q	beta	0.500	0.2000	0.595	0.0183

on the TFP series by Fernald (2014) yields $\rho_a^q = 0.96$ and $\sigma_a^q = 0.79$, where ρ_a^q denotes the quarterly persistence and σ_a^q the quarterly standard deviation of the residuals of the process.

All non-estimated parameters are calibrated as in the previous sections (see Table 2), except π, which is inexistent in Galí (2015) and set to 0.81×4 following Smets and Wouters (2007). Time series for inflation and the effective federal funds rate are sourced from BEA (2025a) and Board of Governors of the Federal Reserve System (US) (2025a). An output gap series is constructed as the percent deviation of real GDP (BEA, 2025c) from potential GDP (U.S. Congressional Budget Office, 2025).

Priors and posteriors for the estimated parameters are reported in Table 3. As for the TFP shock parameters, the superscript q indicates that the estimate relate to a period length of one quarter. For both standard deviations and persistence parameters, prior distributions are adopted from Smets and Wouters (2007). The estimated demand shock is relatively large and persistent, with a standard deviation of 1.83 and a quarterly persistence of 0.94. Both parameters are smaller for the monetary policy shock, with a standard deviation of 0.53 and a quarterly persistence of 0.60.

In the discrete model's shock processes (7)–(9), a parameter ρ_i with $i \in \{z, a, v\}$ quantifies annual persistence, and σ_i measures the standard deviation of the daily innovation ε_t^i. Therefore, the estimated quarterly parameters need to be transformed before being used to simulate daily shock series. Details are laid out in Appendix G.

5.2 Simulation and Results

Based on estimated standard deviations and persistence parameters, I simulate the processes for a demand, supply, and monetary policy shocks across $S = 100,000$ periods. A burn-in period of 10,000 periods is discarded to get rid of the influence of the initial steady state on shock processes. The large number of simulation periods ensures that results do not hinge on the seed underlying the generation of exogenous innovations ε_t^i, which is confirmed in a robustness analysis in Appendix H. Simulated shock series are provided in Figure 9 for two out of approximately 274 simulated years.

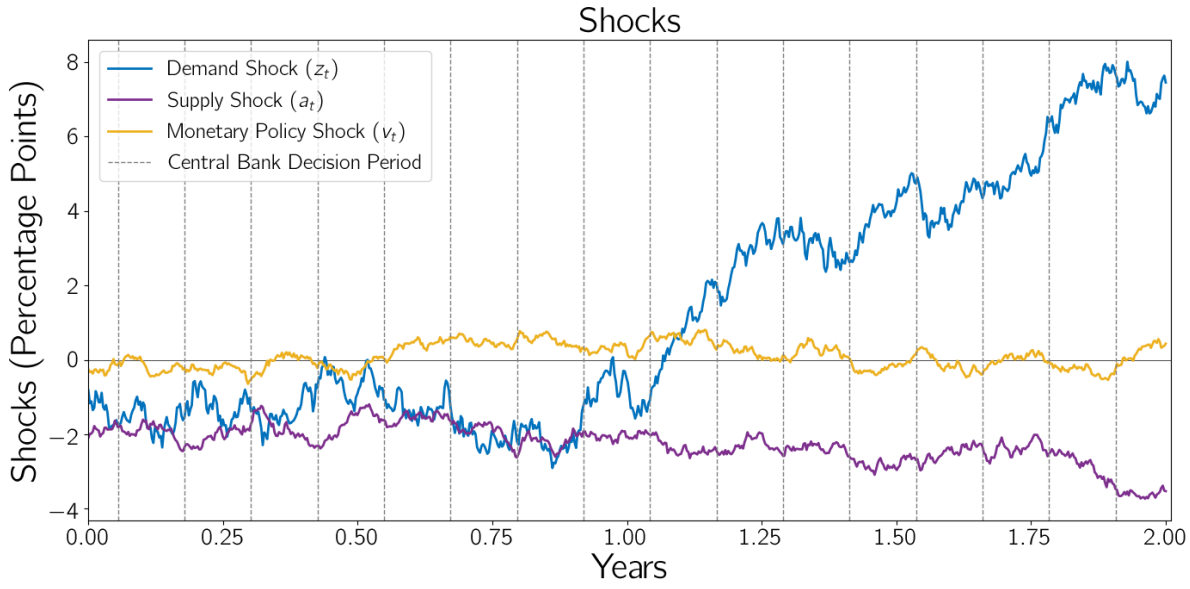


Figure 9: Shocks underlying the simulated business cycle, shown for 2 out of 274 years.

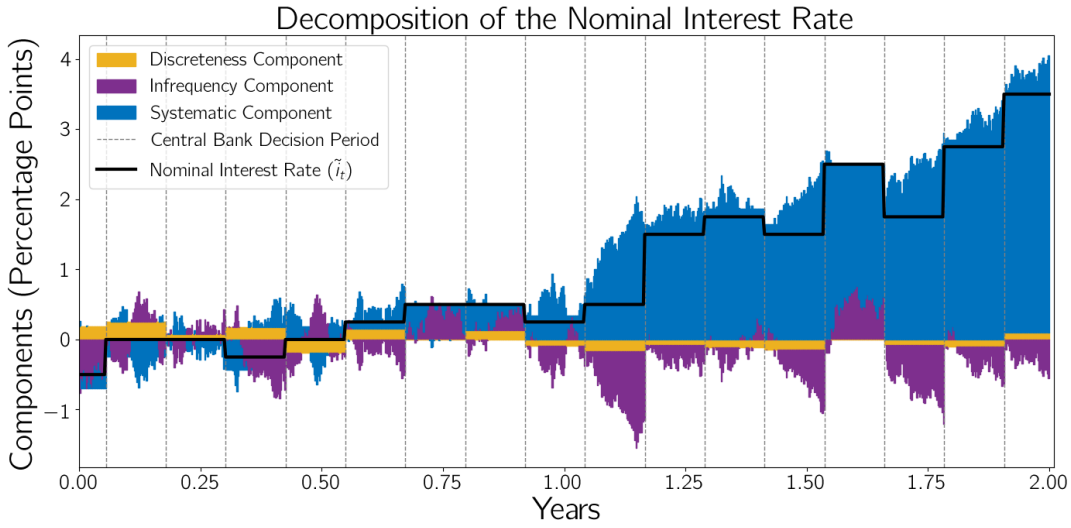
Table 4: Variance decomposition of the simulated business cycle.

	Share of Variance Explained by Component (%)			
	Discreteness	Infrequency	Systematic	Total
Interest Rate	-0.80	0.19	100.61	100.00
Output Gap	1.95	-1.47	99.53	100.00
Inflation	-2.36	-2.11	104.47	100.00

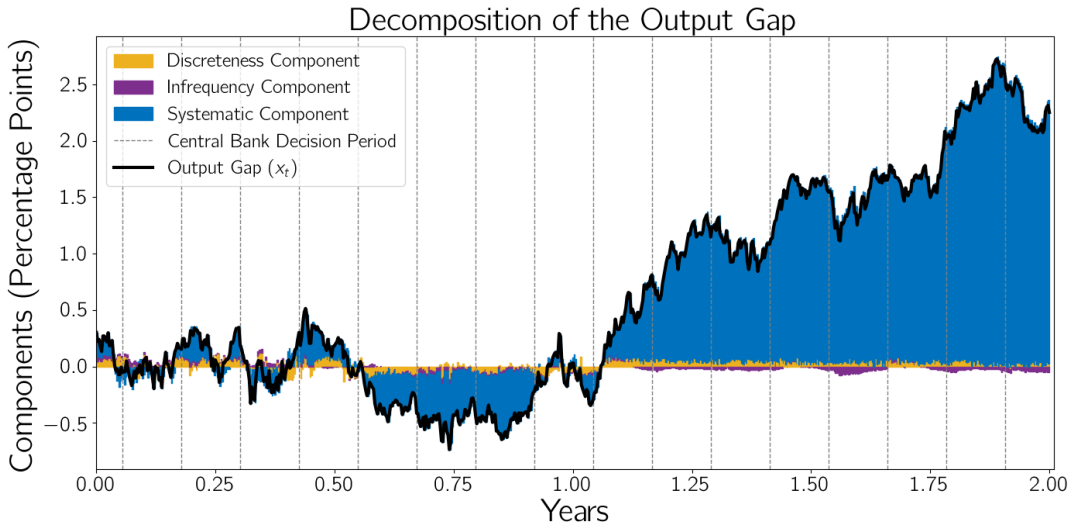
To solve the model during the business cycle, I use the backward model solution described in Section 3.3. Specifically, I treat each period $s \in \{0, \Delta, \ldots, S\Delta\}$ of the simulated business cycle as the first period in a backward solution, again with a terminal condition imposed after 10,000 periods. Thus, in every period s, households expect contemporaneous shocks z_s, a_s, and v_s to decay according to their laws of motion, but then transition to period $s + \Delta$ and observe a new combination of shocks.

Figure 10 plots resulting time series for the interest rate, the output gap, and inflation, where the same two years as for simulated shock processes shown in Figure 9 are selected. The decomposition follows the same method as for impulse responses in Section 4. In Table 4, results of a variance decomposition of all variables across all 90,000 remaining periods are presented.

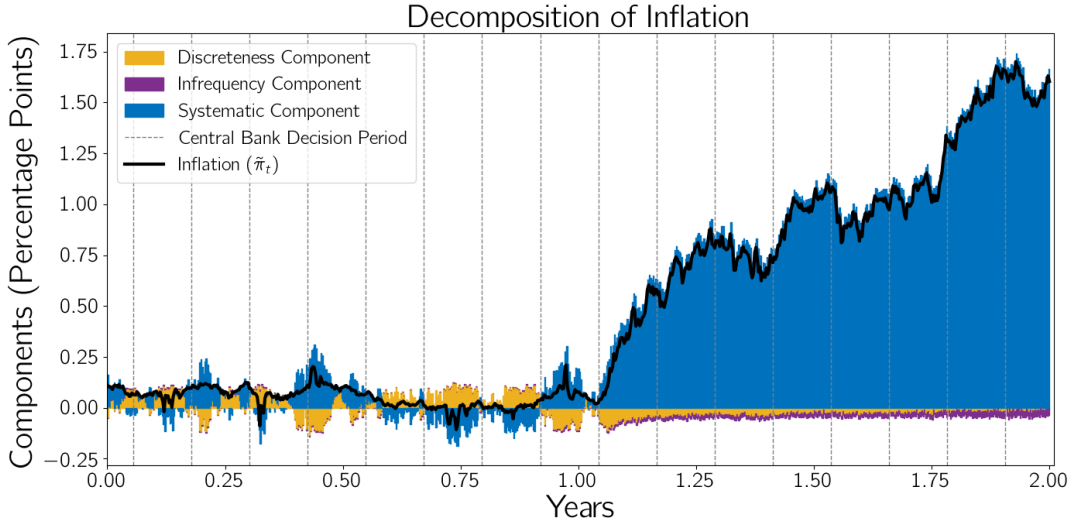
Key findings are as follows. First, the interest rate is significantly affected by discreteness and infrequency, with an average difference between the full discrete model and the systematic component of 33.45 basis points. Discreteness has a visible effect in most meeting intervals, lowering the interest rate variance by -0.80%. The infrequency component tends to build up between central bank meetings and drops to zero when the monetary authority can reset rates, explaining 0.19% of interest rate variance in total.



(a) Interest rate.



(b) Output gap.



(c) Inflation.

Figure 10: Decomposition of model variables during the simulated business cycle, shown for 2 out of 274 years.

Second, the components' effects translate to the real economy, i.e., the output gap. Here, signs are reversed: Discreteness accounts for 1.95% of output gap variance, whereas infrequency explains a negative share of -1.47%. These numbers are broadly reflected in Figure 10b, where the discreteness component has the same and the infrequency component the opposite sign than the output gap itself in most periods.
Third, effects of both components are even more pronounced and clearly negative for inflation, with discreteness accounting for -2.36% and infrequency for -2.11% of its variance.
How can these findings be explained? For infrequency, it was derived already in Section 4.2 that it causes a more active monetary policy on average. Therefore, it is unsurprising that both output-gap- and inflation-variance shares explained by the infrequency component are negative. Additionally, the interest rate set before the first central bank meeting was set to the steady-state level when computing impulse responses in Section 4.2, resulting in an initially inactive monetary policy and a larger deviation from steady state at least for the output gap. During the business cycle, however, even this small amplifying effect of infrequency on volatility is missing, as the interest rate is in general not stuck at its steady-state level when a shock materializes.
Regarding discreteness, opposite effects on the output gap and inflation are in line with the previous analysis of impulse response functions. Specifically, the results presented in Section 4.2 showed that the output gap is influenced by the interest rate path in the relatively close future, whereas inflation is rather driven by expected monetary policy in the long run—a natural finding given that the interest rate directly enters the IS curve (4) but not the Phillips curve (5). As the sign of the discreteness component switches signs multiple times over the expected interest rate path, this explains heterogeneous outcomes for the output gap and inflation (see Figure 7).
Note that the share of any variable that is explained by discreteness is larger in times of small deviations from the steady state, as visible in Figure 10. Again, this is in line with the previous decomposition of impulse responses. Thus, discrete monetary policy has a larger effect in less volatile economies.

5.3 Actual and Effective Monetary Policy Shocks

The transmission of monetary policy shocks is of particular interest to policymakers. As described in Section 3.2, the underlying monetary policy shock process v_t is, in general, not equal to the observed difference between discrete Taylor rules evaluated with and without this shock on the last meeting date. This residual is instead defined as the

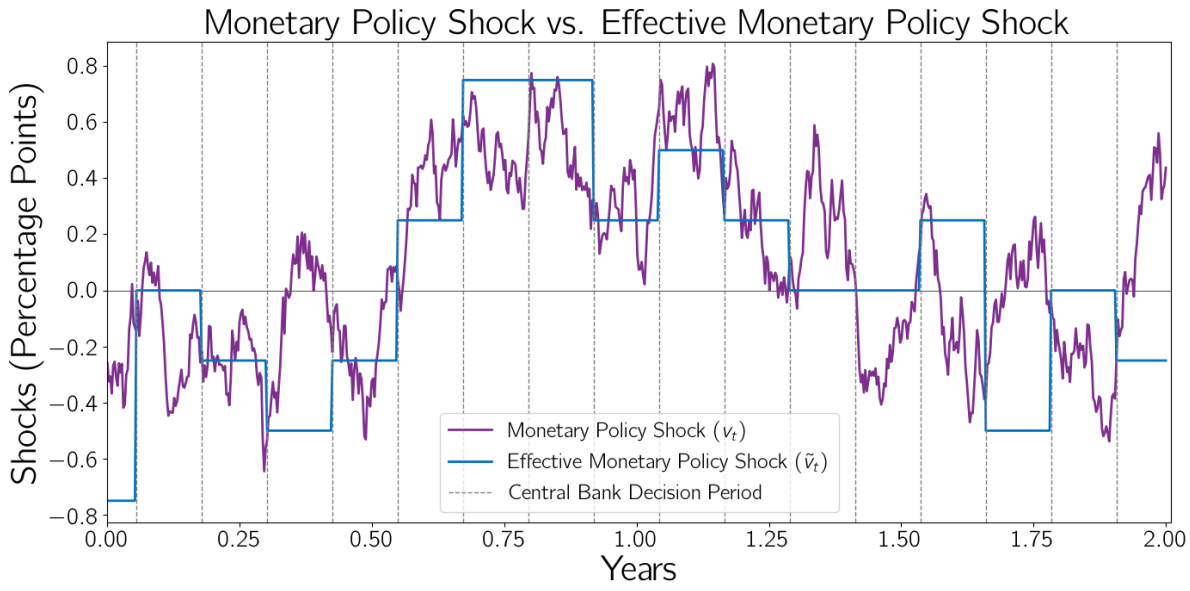


Figure 11: Actual and effective monetary policy shocks during the simulated business cycle, shown for 2 out of 274 years.

effective monetary policy shock $\tilde{v}_t$, formally given by (13):

$$\tilde{v}_t = \begin{cases} \mathcal{D}\left(\tilde{\pi}_{m_t^+-\Delta}, x_{m_t^+-\Delta}, v_t\right) - \mathcal{D}\left(\tilde{\pi}_{m_t^+-\Delta}, x_{m_t^+-\Delta}, 0\right) & \text{if } t \in M, \\ \tilde{v}_{t-\Delta} & \text{else.} \end{cases}$$

I found that $\tilde{v}_t$ is a multiple of 25 basis points and may be either larger or smaller than v_t, depending on the expected output-gap and inflation paths during a meeting period. Thus, the mapping from v_t to $\tilde{v}_t$ constitutes an additional channel through which monetary policy influences the economy in the discrete model. In the following, I evaluate the relevance of this channel over the business cycle.

Both v_t and $\tilde{v}_t$ are shown in Figure 11 for the time period used to plot all shocks and model variables in Figures 9 and 10. The effective monetary policy shock broadly follows the underlying process v_t, but significant differences are evident, particularly between meeting periods.

When aggregated across the entire time range, $\tilde{v}_t$ is only marginally more volatile than v_t (estimated standard deviations of 0.6906 vs. 0.6866) and only slightly larger on average (0.5427 vs. 0.5415 in absolute value). However, the share of the difference between the linear- and discrete-model interest rates that can be explained by the difference between both shocks, $\frac{\tilde{v}_t - v_t}{i_t - i_t^{\text{systematic}}}$, amounts to 13% on average. Therefore, the non-identity of v_t and $\tilde{v}_t$ alone causes a mean deviation of the interest rate from the linear-model benchmark of approximately 4.3 basis points.

6 Conclusion

This paper provides the first systematic analysis of discrete monetary policy. I distinguish two dimensions of discreteness. First, central banks set their interest rates on a grid, typically in increments of 25 basis points. Second, they adjust interest rates at discrete points in time, usually eight times per year.

When interest rates are set on a discrete grid and this is anticipated by economic agents, deviations from a continuous rule solely to remain on the grid should not be interpreted as monetary policy shocks. Indeed, I found that incorporating discrete interest rate steps into Taylor rule estimations reduces estimated mean residuals by up to one-third. This result holds across four distinct settings drawn from the literature, covering different currency areas, observation periods, and Taylor rule specifications. Moreover, it can be confirmed for the effective federal funds rate since 2022, as it has been as discrete as the target rate in this time period.

The paper's second contribution is the specification of a New-Keynesian DSGE model featuring a discrete interest rate and infrequent rate adjustments. In two periods per quarter, the central bank is allowed to reset the interest rate, which it does by approximating a standard linear Taylor rule on a 25-basis-points grid. In all other periods, the interest rate is given by its lag. One period corresponds to one day, such that intertemporal dynamics can be studied precisely.

The first application of the model was the analysis of impulse response functions. Impulse responses were decomposed, such that the effect of both discreteness and infrequency on each variable could be quantified. I found that infrequency matters primarily for the interest rate and only prior to the first central bank decision after an MIT shock materializes. As the model is forward-looking, infrequency only has a minor impact on output gap and inflation. If at all, it rather reduces these variables' deviations from steady state, since it makes monetary policy slightly more active on average.

In contrast, discreteness substantially alters the interest rate response and thereby output gap and inflation dynamics. Specifically, the output gap response to shocks is U-shaped and kinky, and the decay of the inflation response is significantly delayed and rather linear than geometric. Over time, the discreteness component switches signs multiple times for the interest rate and once for the output gap and inflation. I further showed that these effects do not scale linearly in the shock size, rendering overall impulse responses for all variables inhomogeneous and making it difficult to derive general conclusions.

To overcome these issues and to quantify the effects of discreteness and infrequency, I simulated the model across the business cycle. For this exercise, parameters governing exogenous shock processes were estimated for the linear version of the model based on U.S. data on the output gap, inflation, and the effective federal funds rate between 1966 and 2004. During this period, the effective federal funds rate was not yet discrete

and was adjusted continuously on the interbank market, such that discrete features of monetary policy did not need to be explicitly addressed in the estimation approach. Results indicate that the interest rate is considerably affected by discrete monetary policy, with a mean absolute difference of 33 basis points between the discrete model and the linear benchmark. Discreteness accounts for approximately 2.0% of output-gap variance, whereas inflation variance is reduced by 2.4%, which confirms heterogeneous findings for these variables derived for impulse responses. Infrequency rather reduces volatility for both variables.

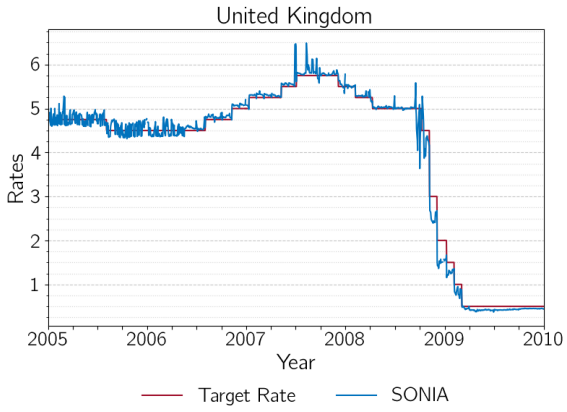
Of particular interest to policymakers is the transmission of monetary policy shocks over the business cycle. In the discrete model, continuous monetary policy shocks entering the underlying linear Taylor rule are unobservable to agents. Instead, they observe only *effective* monetary policy shocks, defined as the difference between the realized rate and the discrete rule evaluated in the absence of a monetary policy shock. By construction, these surprises are multiples of 25 basis points themselves. I find that the discrepancy between effective and underlying monetary policy shocks alone generates an average deviation of the interest rate from the linear benchmark of more than 4 basis points.

The model offers various opportunities for further research. Most importantly, the paper takes observed monetary policy with infrequent and discrete rate adjustments as given. An extended framework could explicitly model tradeoffs to rationalize observed interest rate setting. For instance, adjusting rates more often could require the costly collection of information, and high-frequency data may be noisy. Moreover, setting interest rates in increments of 25 basis points may simplify central bank communication by providing clearer signals to markets. This is in line with my reduced-form estimation results—as soon as discreteness was incorporated, monetary policy shocks often dropped to zero. In this sense, discrete interest rate steps may be seen as a device to reduce uncertainty. Determining the optimal decision interval and interest rate step size resulting from these tradeoffs is left for further research.

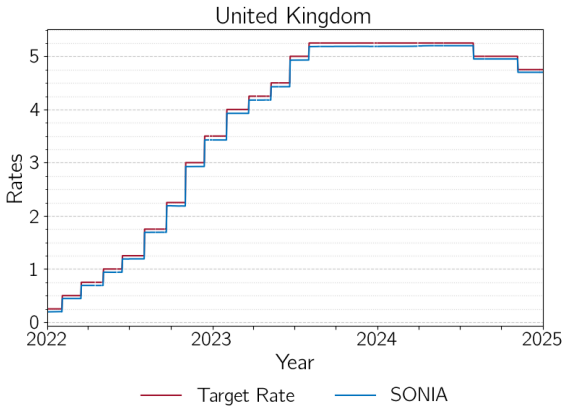
Appendix

A Relation of Target Rates and Overnight Market Rates for the United Kingdom and Switzerland

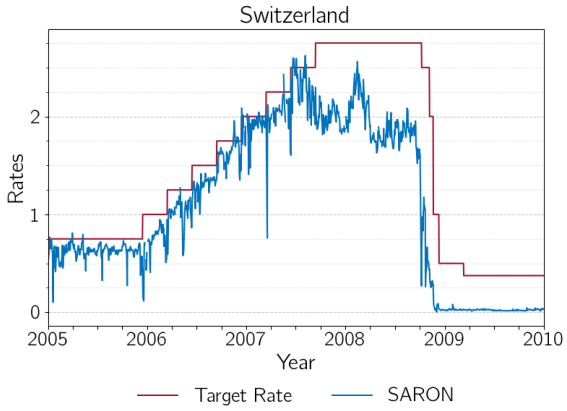
Figure 12 illustrates the relationship between target rates and overnight market rates for the United Kingdom and Switzerland, both before and after the zero lower bound (ZLB) period. For corresponding figures for the United States and the euro area, see Figure 2 in the main text.



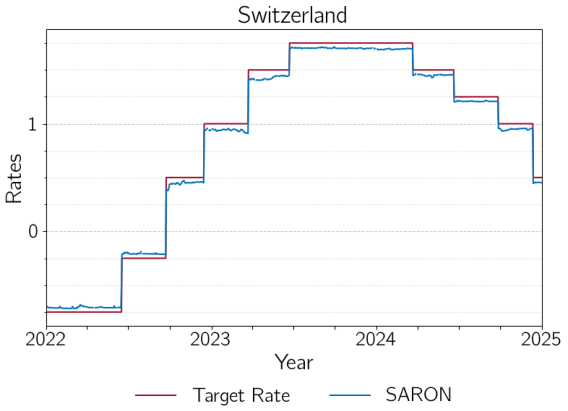
(a) United Kingdom, 2005–2010. Source: BIS (2025), Bank of England (2025).



(b) United Kingdom, 2022–2025. Source: BIS (2025), Bank of England (2025).



(c) Switzerland, 2005–2010. Source: BIS (2025), Swiss National Bank (2025).



(d) Switzerland, 2022–2025. Sources: BIS (2025), Swiss National Bank (2025).

Figure 12: Policy rates and overnight market rate indices for the United Kingdom and Switzerland, with discrete market rates since 2022.

Table 5: Reduced-form Taylor rule estimations: Data sources.

Variable	Source
Target Rate	BIS (2025)
Output Gap	Taylor (1993): Percent deviation of real GDP (BEA, 2025c) from its trend Judd and Rudebusch (1998): Percent deviation of real GDP (BEA, 2025c) from potential GDP (U.S. Congressional Budget Office, 2025) Belke and Polleit (2007), FED: HP-filtered cycle component of real GDP (BEA, 2025c) Belke and Polleit (2007), ECB: HP-filtered cycle component of real GDP (Eurostat, 2025b) Clarida et al. (1998): Log industrial prod., resid. of quadr. trend (Japan 1979–1994: OECD (2025), U.S. 2022–2025: Board of Governors of the Federal Reserve System (2025b))
Inflation	Judd and Rudebusch (1998) and Taylor (1993): GDP deflator (BEA, 2025a) Belke and Polleit (2007), FED: CPI (OECD, 2025b) Belke and Polleit (2007), ECB: CPI (Eurostat, 2025a) Clarida et al. (1998): CPI (Japan 1979–1994: OECD (2025a)), PCEPI (U.S. 2022–2025: BEA (2025b))

Note: For Coibion and Gorodnichenko (2011), data from their replication package were used for all variables.

B Details on Taylor Rule Estimation and Data

This appendix provides details on the methods and data used to estimate the linear and discrete Taylor rules presented in Section 2. Additionally, it describes the estimation approach and results for a discrete Taylor rule on a 6.25-basis-points grid during the period from 1987Q1 to 1989Q4, following Taylor (1993).

In all estimated Taylor rules, the output gap and inflation (including leads or lags for some specifications) appear as exogenous variables. Furthermore, the rules include the target rate both as the dependent variable and one or two of its lags as independent variables. The underlying data for all these variables are listed in Table 5.

For the example of Clarida et al. (1998), who use 12-month-ahead inflation as an explanatory variable, I follow their approach and instrument future inflation and the current output gap by lags 1–6, 9, and 12 of the output gap, inflation, and the target rate. The authors additionally employed real exchange rates and a world commodity price variable as instruments; however, I maintain consistency with the variable set used across all estimations.

C Estimation of a Discrete Version of the Taylor (1993) Rule

Linear and discrete Taylor rules for the period 1987Q1 to 1989Q4 are estimated for the specification

$$i_t = \beta_0 + \beta_1 \pi_t + \beta_2 x_t + \varepsilon_t,$$

Table 6: Model fit statistics for estimated linear and discrete Taylor rules based on Taylor (1993), U.S., 1987Q1–1989Q4.

MSE		MAE		Share of Zero Resid.
(Linear)	**(Discrete)**	**(Linear)**	**(Discrete)**	**(Discrete)**
0.1966	0.1849	0.3969	0.3854	0.00

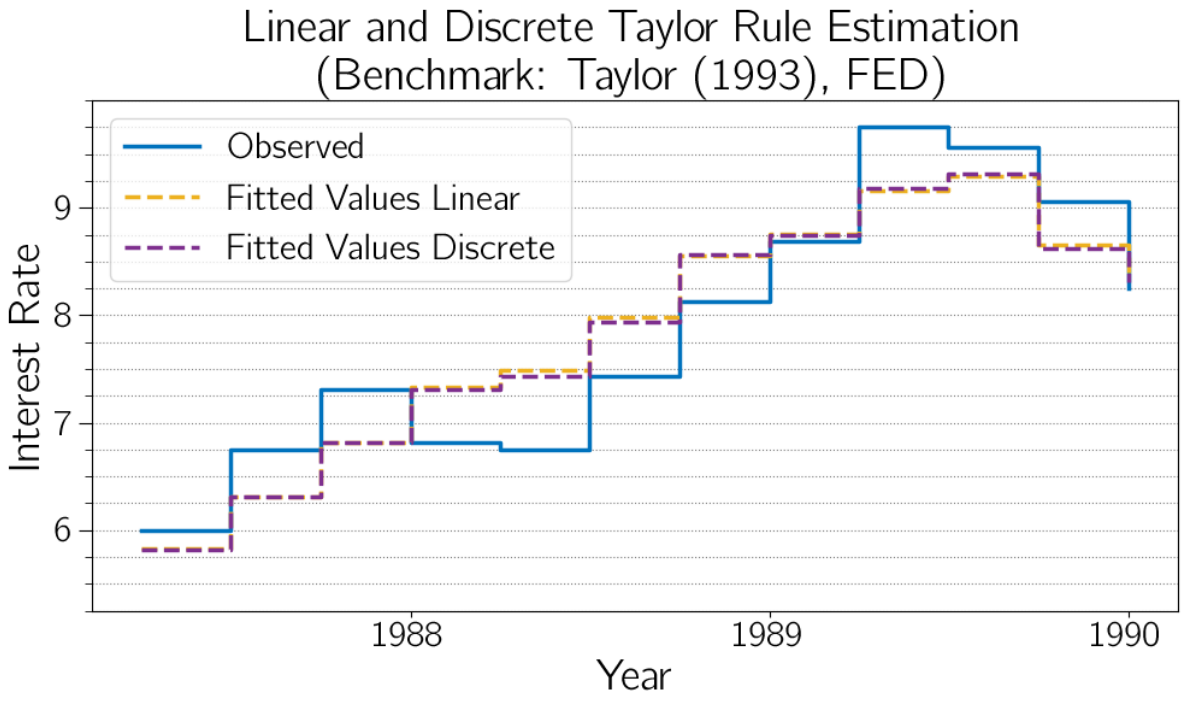


Figure 13: Fitted values for estimated linear and discrete Taylor rules, based on Taylor (1993), FED, 1987Q1–1989Q4.

following Taylor (1993). In contrast to Section 2, the interest rate grid for the discrete rule is defined as $I = \{\ldots, -0.125, -0.065, 0, 0.065, 0.125, \ldots\}$, reflecting the FED's pre-1990 practice to adjust the target rate in 6.25-basis-points steps. As since 1990 only adjustments in 25-basis-points increments have been observed, I restrict the sample accordingly, shortening the sample period compared to Taylor (1993).

Estimation results are presented in Table 6. As for most of the examples discussed in Section 2 and shown in Table 1, the discrete rule is superior to the linear one in terms of all model fit statistics. However, differences are small, the discrete rule does not yield zero residuals in any period, and fitted values for both rules are visually almost indistinguishable (see Figure 13). This seems to confirm that the relative advantage of the discrete rule decreases when the interest step size is reduced. In the extreme case, with the interest rate increment converging to zero, the discrete rule would become equivalent to a linear rule.

D Derivation of IS and Phillips Curve

The derivation of the IS and Phillips curve presented here closely follows Galí (2015), Chapter 2.1 and Chapter 3, with three main differences. First, the period length is set to Δ instead of one. Second, bonds purchased in period t that mature in period $t+\Delta$ yield interest $(1+i_{t+\Delta})$ rather than $(1+i_t)$. Finally, there is an inflation target $\pi \neq 0$.

D.1 Derivation of the Consumption Euler Equation in Logs

The household maximizes lifetime utility

$$\mathbb{E}_0 \sum_{t \in \{0,\Delta,2\Delta,\dots\}} \beta^t U\left(C_t, N_t; Z_t\right) \tag{17}$$

subject to the budget constraint

$$P_t C_t + B_t \leq (1+i_t)^{\Delta} B_{t-\Delta} + W_t N_t + D_t \tag{18}$$

and a No-Ponzi condition. Here, C_t denotes consumption, N_t hours worked, and Z_t a preference (demand) shock. P_t denotes the price level, B_t bonds, i_t the nominal interest rate, W_t the nominal wage, and D_t dividends. The parameter β is the discount factor. The resulting optimality conditions are

$$-\frac{U_{n,t}}{U_{c,t}} = \frac{W_t}{P_t} \tag{19}$$

$$U_{c,t} = \beta^{\Delta} \mathbb{E}_t U_{c,t+\Delta} \left(1+i_{t+\Delta}\right)^{\Delta} \frac{P_t}{P_{t+\Delta}} \tag{20}$$

and a transversality condition.
Preferences are given by

$$U\left(C_t, N_t; Z_t\right) = \begin{cases} \left(\frac{C_t^{1-\sigma}-1}{1-\sigma} - \frac{N_t^{1+\varphi}}{1+\varphi}\right) Z_t & \text{for } \sigma \neq 1, \\ \left(\log C_t - \frac{N_t^{1+\varphi}}{1+\varphi}\right) Z_t & \text{for } \sigma = 1. \end{cases} \tag{21}$$

Here, φ denotes the Frisch elasticity of labor supply, and σ denotes the inverse of the intertemporal elasticity of substitution.
Then, the optimality conditions (20) can be written as

$$\frac{N_t^{\varphi}}{C_t^{-\sigma}} = \frac{W_t}{P_t},$$

$$1 = \beta^{\Delta} \mathbb{E}_t \left(\frac{C_{t+\Delta}}{C_t}\right)^{-\sigma} \frac{Z_{t+\Delta}}{Z_t} \left(1+i_{t+\Delta}\right)^{\Delta} \frac{P_t}{P_{t+\Delta}}.$$

Take logs:

$$\varphi n_t + \sigma c_t = w_t - p_t, \tag{22}$$

$$0 = \Delta \log \beta - \sigma \left(\mathbb{E}_t c_{t+\Delta} - c_t \right) + \mathbb{E}_t z_{t+\Delta} - z_t + \Delta \mathbb{E}_t i_{t+\Delta} - \mathbb{E}_t \log \left(\frac{P_{t+\Delta}}{P_t} \right). \tag{23}$$

Let π_t denote the **annualized** inflation rate at time t, such that $\log \left(\frac{P_t}{P_{t-\Delta}} \right) = \Delta \pi_t$. Then, use (7) to find $\mathbb{E}_t z_{t+\Delta} = \rho_z^{\Delta} z_t$, and define the natural real rate in steady state as $\rho := -\log \beta$. This yields

$$c_t = \mathbb{E}_t c_{t+\Delta} - \frac{\Delta}{\sigma} \mathbb{E}_t \left(i_{t+\Delta} - \pi_{t+\Delta} - \rho \right) + \frac{1}{\sigma} \left(1 - \rho_z^{\Delta} \right) z_t \tag{24}$$

as the log-linearized intertemporal consumption Euler equation.

D.2 Derivation of the Phillips Curve as a Function of Markups

The price level in period t is given as

$$P_t = \left[\theta^{\Delta} \left(P_{t-\Delta} \right)^{1-\epsilon} + \left(1 - \theta^{\Delta} \right) \left(P_t^{\star} \right)^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}},$$

where θ is the fraction of firms that cannot reset the price in an entire year and $P_t^{\star}$ is the price optimally set in period t.
To introduce a stationary inflation variable, divide the interest rate by a trend price level $\bar{P}_t$. Define $\tilde{P}_t = \frac{P_t}{\bar{P}_t}$, $\tilde{P}_t^{\star} = \frac{P_t^{\star}}{\bar{P}_t}$ as stationary price level variables:

$$\tilde{P}_t = \left[\theta^{\Delta} \left(\tilde{P}_{t-\Delta} \frac{\bar{P}_{t-\Delta}}{\bar{P}_t} \right)^{1-\epsilon} + \left(1 - \theta^{\Delta} \right) \left(\tilde{P}_t^{\star} \right)^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}.$$

Trend price inflation should be consistent with the central bank's inflation target. If the inflation target π is given in annualized terms, this implies $(1+\pi)^{\Delta} = \frac{\bar{P}_t}{\bar{P}_{t-\Delta}}$:

$$\tilde{P}_t = \left[\theta^{\Delta} \left(\tilde{P}_{t-\Delta} \left(1 + \pi \right)^{-\Delta} \right)^{1-\epsilon} + \left(1 - \theta^{\Delta} \right) \left(\tilde{P}_t^{\star} \right)^{1-\epsilon} \right]^{\frac{1}{1-\epsilon}}.$$

Rearrange:

$$\begin{aligned}
\left(\tilde{P}_t\right)^{1-\epsilon} &= \theta^{\Delta}\left(\tilde{P}_{t-\Delta}\left(1+\pi\right)^{-\Delta}\right)^{1-\epsilon} + \left(1-\theta^{\Delta}\right)\left(\tilde{P}_t^{\star}\right)^{1-\epsilon}, \\
\left(\frac{\tilde{P}_t}{\tilde{P}_{t-\Delta}}\right)^{1-\epsilon} &= \theta^{\Delta}\left(1+\pi\right)^{\Delta(\epsilon-1)} + \left(1-\theta^{\Delta}\right)\left(\frac{\tilde{P}_t^{\star}}{\tilde{P}_{t-\Delta}}\right)^{1-\epsilon}, \\
\left(1+\tilde{\pi}_t\right)^{\Delta(1-\epsilon)} &= \theta^{\Delta}\left(1+\pi\right)^{\Delta(\epsilon-1)} + \left(1-\theta^{\Delta}\right)\left(\frac{\tilde{P}_t^{\star}}{\tilde{P}_{t-\Delta}}\right)^{1-\epsilon}.
\end{aligned}$$

Log-linearize to find

$$\Delta\tilde{\pi}_t = \left(1-\theta^{\Delta}\right)\left(\tilde{p}_t^{\star} - \tilde{p}_{t-\Delta}\right). \tag{25}$$

The firm's price setting problem is given as

$$\begin{aligned}
&\max_{P_t^{\star}} \sum_{k=0}^{\infty} \theta^{\Delta k}\mathbb{E}_t\left\{\Lambda_{t|t+\Delta k}Y_{t+\Delta k|t}\left(\frac{P_t^{\star}}{P_{t+\Delta k}} - \Psi_{t+\Delta k}\right)\right\} \\
&\quad \text{s.t.} \\
&Y_{t+\Delta k|t} = \left(\frac{P_t^{\star}}{P_{t+\Delta k}}\right)^{-\epsilon} C_{t+\Delta k},
\end{aligned}$$

where $\Lambda_{t,t+\Delta k} \equiv \beta^{\Delta k}\frac{U_{c,t+\Delta k}}{U_{c,t}}$ is the stochastic discount factor, Ψ_t are real marginal costs per unit of output (nominal marginal costs: $\mathcal{C} = P_{t+\Delta k}\Psi_{t+\Delta k}$), and $Y_{t+\Delta k|t}$ denotes output in period $t+\Delta k$ for a firm that last reset its price in period t.
Rewrite for stationary price levels:

$$\begin{aligned}
&\max_{\tilde{P}_t^{\star}} \sum_{k=0}^{\infty} \theta^{\Delta k}\mathbb{E}_t\left\{\Lambda_{t|t+\Delta k}Y_{t+\Delta k|t}\left(\frac{\tilde{P}_t^{\star}}{\tilde{P}_{t+\Delta k}}\left(1+\pi\right)^{-\Delta k} - \Psi_{t+\Delta k}\right)\right\} \\
&\quad \text{s.t.} \\
&Y_{t+\Delta k|t} = \left(\frac{\tilde{P}_t^{\star}}{\tilde{P}_{t+\Delta k}}\left(1+\pi\right)^{-\Delta k}\right)^{-\epsilon} C_{t+\Delta k}.
\end{aligned}$$

Take the first-order condition and use goods market clearing, i.e., $C_{t+\Delta k} = Y_{t+\Delta k}$:

$$\begin{aligned}
\sum_{k=0}^{\infty} \theta^{\Delta k}\mathbb{E}_t\{\Lambda_{t,t+\Delta k}\Bigg[&(1-\epsilon)\left(\tilde{P}_t^{\star}\right)^{-\epsilon}\left(\frac{\left(1+\pi\right)^{-\Delta k}}{\tilde{P}_{t+\Delta k}}\right)^{1-\epsilon} Y_{t+\Delta k} \\
&+\epsilon\Psi_{t+\Delta k}\left(\tilde{P}_t^{\star}\right)^{-\epsilon-1}\left(\frac{\left(1+\pi\right)^{-\Delta k}}{\tilde{P}_{t+\Delta k}}\right)^{-\epsilon} Y_{t+\Delta k}\Bigg]\Bigg\} = 0.
\end{aligned}$$

In steady state, $\Lambda_{t,t+\Delta k} = \beta^{\Delta k}$ and $\frac{\tilde{P}_t^{\star}}{\tilde{P}_{t-\Delta k}} = 1$, and all firms are symmetric: $Y_{t+\Delta k|t} = Y$,

and $\Psi_{t+\Delta k|t} = \Psi_{t+\Delta k} = \Psi$. Thus, log-linearization yields

$$p_t^\star = \log \mathcal{M} + \left(1 - \left(\frac{\beta\theta}{1+\pi}\right)^\Delta\right) \sum_{k=0}^{\infty} \left(\frac{\theta\beta}{1+\pi}\right)^{\Delta k} \psi_{t+\Delta k|t}, \tag{26}$$

with $\psi_t = \log \Psi_t$.
In any period, the average marginal cost ψ_t is given by

$$\psi_t = \left(1 - \theta^\Delta\right) \psi_{t|t} + \theta^\Delta \psi_{t-\Delta}$$

Iterating on this equation yields

$$\psi_t = \left(1 - \theta^\Delta\right) \sum_{k=0}^{\infty} \theta^{\Delta k} \psi_{t|t-\Delta k}. \tag{27}$$

Technology is given by

$$Y_t(i) = A_t N_t(i)^{1-\alpha}, \tag{28}$$

where A_t is exogenous total factor productivity (TFP). Thus, the marginal product of labor is

$$\text{MPN}_t(i) = (1-\alpha)\, A_t N_t(i)^{-\alpha},$$

or, in logs,

$$\text{mpn}_t(i) = \log(1-\alpha) + a_t - \alpha n_t(i).$$

Therefore, the log real marginal cost of a firm which last set its price in period t is given by

$$\psi_{t+\Delta k|t} = w_{t+\Delta k} - p_{t+\Delta k} - \text{mpn}_{t+\Delta k|t} \tag{29}$$

$$= w_{t+\Delta k} - p_{t+\Delta k} - \left(a_{t+\Delta k} - \alpha n_{t+\Delta k|t} + \log(1-\alpha)\right), \tag{30}$$

with $w_{t+\Delta k} - p_{t+\Delta k}$ being the log real wage in period $t + \Delta k$.
Note that we can likewise determine the average real marginal cost in the economy at time t as

$$\psi_t = w_t - p_t - (a_t - \alpha n_t + \log(1-\alpha)). \tag{31}$$

Aggregate employment is given by

$$N_t = \int_0^1 N_t(i)di$$

Combining this with (28) yields

$$\begin{aligned} N_t &= \int_0^1 \left(\frac{Y_t(i)}{A_t}\right)^{\frac{1}{1-\alpha}} di \\ &= \left(\frac{Y_t}{A_t}\right)^{\frac{1}{1-\alpha}} \int_0^1 \left(\frac{P_t(i)}{P_t}\right)^{-\frac{\epsilon}{1-\alpha}} di. \end{aligned}$$

In logs,

$$(1-\alpha)\, n_t = y_t - a_t + d_t, \tag{32}$$

where $d_t \equiv (1-\alpha)\log\int_0^1 \left(\frac{P_t(i)}{P_t}\right)^{-\frac{\epsilon}{1-\alpha}} di$ is a measure of price dispersion equal to zero up to a first-order approximation.
Thus,

$$n_t = \frac{1}{1-\alpha}\left(y_t - a_t\right). \tag{33}$$

We can relate (30) to (31) as

$$\begin{aligned} \psi_{t+\Delta k|t} &= \psi_{t+\Delta k} + \alpha\left(n_{t+\Delta k|t} - n_{t+\Delta k}\right) \\ \overset{(33)}{\Leftrightarrow}\ \psi_{t+\Delta k|t} &= \psi_{t+\Delta k} + \frac{\alpha}{1-\alpha}\left(y_{t+\Delta k|t} - y_{t+\Delta k}\right). \end{aligned}$$

Use the goods demand function to determine $y_{t+\Delta k|t} - y_{t+\Delta k}$:

$$\begin{aligned} Y_{t+\Delta k|t} &= \left(\frac{\tilde{P}_t^\star}{\tilde{P}_{t+\Delta k}}(1+\pi)^{-\Delta k}\right)^{-\epsilon} C_{t+\Delta k} \\ \Rightarrow y_{t+\Delta k|t} &= -\epsilon\left(\tilde{p}_t^\star - \tilde{p}_{t+\Delta k} - \Delta k\pi\right) + c_{t+\Delta k}. \end{aligned}$$

Thus, any firm that could reset its price in period t will have set $p_t^\star$ as its price and

$$y_{t+\Delta k|t} - y_{t+\Delta k} = -\epsilon\left(\tilde{p}_t^\star - \tilde{p}_{t+\Delta k} - \Delta k\pi\right),$$

such that

$$\psi_{t+\Delta k|t} = \psi_{t+\Delta k} - \frac{\alpha\epsilon}{1-\alpha}\left(\tilde{p}_t^\star - \tilde{p}_{t+\Delta k} - \Delta k\pi\right).$$

Use this in (26) to find

$$p_t^\star = \log \mathcal{M} + \left(1 - \left(\frac{\theta\beta}{1+\pi}\right)^\Delta\right) \sum_{k=0}^{\infty} \left(\frac{\theta\beta}{1+\pi}\right)^{\Delta k} \mathbb{E}_t \left\{\psi_{t+\Delta k} - \frac{\alpha\epsilon}{1-\alpha}\left(\tilde{p}_t^\star - \tilde{p}_{t+\Delta k} - \Delta k\pi\right)\right\}.$$

Rearrange to have $p_t^\star$ on the left-hand side only, substitute $\psi_{t+\Delta k} = \tilde{p}_{t+\Delta k} - \log \mathcal{M}_{t+\Delta k}$, and define $\Theta = \frac{1-\alpha}{1-\alpha+\alpha\epsilon}$ to obtain

$$p_t^\star = \left(1 - \left(\frac{\theta\beta}{1+\pi}\right)^\Delta\right) \sum_{k=0}^{\infty} \left(\frac{\theta\beta}{1+\pi}\right)^{\Delta k} \mathbb{E}_t \left\{\tilde{p}_{t+\Delta k} - \Theta\left(\log \mathcal{M}_{t+\Delta k} - \log \mathcal{M}\right) + \frac{\alpha\epsilon}{1+\alpha\epsilon-\alpha}\Delta k\pi\right\}.$$

Iterating one period forward yields $\mathbb{E}_t p_{t+\Delta}^\star$, and one can rewrite the equation recursively as

$$p_t^\star = \left(\frac{\beta\theta}{1+\pi}\right)^\Delta \mathbb{E}_t\{p_{t+\Delta}^\star\} + \left(1 - \left(\frac{\beta\theta}{1+\pi}\right)^\Delta\right)\left(\tilde{p}_t - \Theta\left(\log \mathcal{M}_t - \log \mathcal{M}\right)\right).$$

Use this in (25):

$$\Delta\tilde{\pi}_t = \left(1-\theta^\Delta\right)\left[\left(\frac{\beta\theta}{1+\pi}\right)^\Delta \mathbb{E}_t p_{t+\Delta}^\star + \left(1 - \left(\frac{\beta\theta}{1+\pi}\right)^\Delta\right)\left(\tilde{p}_t - \Theta\left(\log \mathcal{M}_t - \log \mathcal{M}\right)\right) - \tilde{p}_{t-\Delta}\right].$$

Note that $\Delta\tilde{\pi}_t = \tilde{p}_t - \tilde{p}_{t-\Delta}$ (recall that $\tilde{\pi}_t$ denotes the *annualized* stationarized inflation rate) and (25) implies $\mathbb{E}_t\tilde{p}_{t+\Delta}^\star - \tilde{p}_t = \frac{\Delta\mathbb{E}_t\tilde{\pi}_{t+\Delta}}{1-\theta^\Delta}$. Then,

$$\tilde{\pi}_t = \left(\frac{\beta}{1+\pi}\right)^\Delta \mathbb{E}_t\tilde{\pi}_{t+\Delta} - \underbrace{\frac{\left(1-\theta^\Delta\right)\left(1-\left(\frac{\beta\theta}{1+\pi}\right)^\Delta\right)}{\Delta\theta^\Delta}}_{\equiv\lambda_{\mathcal{M}}}\Theta\left(\log \mathcal{M}_t - \log \mathcal{M}\right). \tag{34}$$

D.3 Derivation of the Final Phillips Curve

I now relate inflation to the output gap instead of the deviation of markups from steady state. Observe that the period-t log average markup can be written as

$$\begin{aligned} \log \mathcal{M}_t &= -\psi_t \\ \overset{(31)}{\Leftrightarrow} \log \mathcal{M}_t &= -\left(w_t - p_t\right) + \left(a_t - \alpha n_t + \log\left(1-\alpha\right)\right). \end{aligned}$$

Now, use (22) to substitute for $w_t - p_t$ and (33) afterwards to find

$$\log \mathcal{M}_t = -\left(\sigma + \frac{\varphi+\alpha}{1-\alpha}\right) y_t + \left(\frac{1+\varphi}{1-\alpha}\right) a_t + \log\left(1-\alpha\right). \tag{35}$$

Defining y_t^n as output under flexible prices ($\theta = 0$) and recalling that the markup in such a case would be equal to the steady-state markup $\mathcal{M}$, one obtains

$$\log \mathcal{M} = -\left(\sigma + \frac{\varphi + \alpha}{1 - \alpha}\right) y_t^n + \left(\frac{1 + \varphi}{1 - \alpha}\right) a_t + \log(1 - \alpha) \tag{36}$$

$$y_t^n = \psi_{ya} a_t + \psi_y, \tag{37}$$

with $\psi_y \equiv -\frac{(1-\alpha)(\log \mathcal{M} - \log(1-\alpha))}{\sigma(1-\alpha)+\varphi+\alpha}$ and $\psi_{ya} \equiv \frac{1+\varphi}{\sigma(1-\alpha)+\varphi+\alpha}$.
Subtract (36) from (35) to find

$$\log \mathcal{M}_t - \log \mathcal{M} = -\left(\sigma + \frac{\varphi + \alpha}{1 - \alpha}\right)(y_t - y_t^n),$$

which can be used in (34) to arrive at

$$\tilde{\pi}_t = \left(\frac{\beta}{1 + \pi}\right)^{\Delta} \mathbb{E}_t \tilde{\pi}_{t+\Delta} + \kappa x_t, \tag{38}$$

with $\kappa \equiv \lambda_{\mathcal{M}} \left(\sigma + \frac{\varphi+\alpha}{1-\alpha}\right)$ and $x_t \equiv y_t - y_t^n$. This is the final version of the Phillips curve.

D.4 Derivation of the Final IS Curve

Use market clearing in (24) to find

$$y_t = \mathbb{E}_t y_{t+\Delta} - \frac{\Delta}{\sigma} \mathbb{E}_t \left(i_{t+\Delta} - \pi_{t+\Delta} - \rho\right) + \frac{1}{\sigma}\left(1 - \rho_z^{\Delta}\right) z_t$$

Subtract $y_t^n = \psi_{ya} a_t + \psi_y$ on both sides to get the output gap on the left-hand side:

$$x_t = \mathbb{E}_t y_{t+\Delta} - \frac{\Delta}{\sigma} \mathbb{E}_t \left(i_{t+\Delta} - \pi_{t+\Delta} - \rho\right) + \frac{1}{\sigma}\left(1 - \rho_z^{\Delta}\right) z_t - \psi_{ya} a_t - \psi_y.$$

Use $\mathbb{E}_t y_{t+\Delta}^n = \psi_{ya} \rho_a^{\Delta} a_t + \psi_y$. Thus,

$$\begin{aligned} x_t &= \mathbb{E}_t y_{t+\Delta} - \frac{\Delta}{\sigma} \mathbb{E}_t \left(i_{t+\Delta} - \pi_{t+\Delta} - \rho\right) + \frac{1}{\sigma}\left(1 - \rho_z^{\Delta}\right) z_t - \mathbb{E}_t y_{t+\Delta}^n - \psi_{ya}\left(1 - \rho_a^{\Delta}\right) a_t \\ &= \mathbb{E}_t x_{t+\Delta} - \frac{\Delta}{\sigma} \mathbb{E}_t \left(i_{t+\Delta} - \pi_{t+\Delta} - \rho\right) + \frac{1}{\sigma}\left(1 - \rho_z^{\Delta}\right) z_t - \psi_{ya}\left(1 - \rho_a^{\Delta}\right) a_t. \end{aligned}$$

Define $\lambda_z \equiv \frac{1}{\sigma}\left(1 - \rho_z^{\Delta}\right)$ and $\lambda_a \equiv \psi_{ya}\left(1 - \rho_a^{\Delta}\right)$. Then,

$$x_t = \mathbb{E}_t x_{t+\Delta} - \frac{\Delta}{\sigma} \mathbb{E}_t \left(i_{t+\Delta} - \pi_{t+\Delta} - \rho\right) + \lambda_z z_t - \lambda_a a_t.$$

Finally, express $\pi_{t+\Delta}$ in terms of stationary inflation using

$$\pi_{t+\Delta} = \frac{1}{\Delta}\log\left(\frac{P_{t+\Delta}}{P_t}\right) = \frac{1}{\Delta}\log\left(\frac{P_{t+\Delta}}{\bar{P}_{t+\Delta}}\frac{\bar{P}_t}{P_t}\frac{\bar{P}_{t+\Delta}}{\bar{P}_t}\right) = \frac{1}{\Delta}\log\left(\frac{\tilde{P}_{t+\Delta}}{\tilde{P}_t}\frac{\bar{P}_{t+\Delta}}{\bar{P}_t}\right) = \tilde{\pi}_{t+\Delta} + \pi.$$

Define the steady-state nominal rate as $\bar{i} := \pi + \rho$. Then,

$$x_t = \mathbb{E}_t x_{t+\Delta} - \frac{\Delta}{\sigma}\mathbb{E}_t\left(i_{t+\Delta} - \tilde{\pi}_{t+\Delta} - \bar{i}\right) + \lambda_z z_t - \lambda_a a_t.$$

This is the final version of the IS curve.

E Discussion of Timing Assumptions

I deviated from the New-Keynesian model in Galí (2015) not only by adding the discrete components of monetary policy but also by making new assumptions related to time. In the following, I show that these assumptions are not the drivers of central results presented in the main part.

E.1 Shift of Interest Rate Time Index in the IS Curve

The time index of the interest rate entering the IS curve (4) is shifted by one period into the future. In contrast, Galí (2015) proposes a model in which the period-t interest rate is used in the IS curve. Shifting the time index ensures that the model can be solved backward given discrete interest rate steps. Without this assumption, one would face a fixed-point problem that has a solution only in special cases. To see this, consider the model (14) for period $m_t^+ - \Delta$ and use the period-$m_t^+ - \Delta$ interest rate in the IS curve:

$$\begin{aligned}
x_{m_t^+-\Delta} &= \mathbb{E}_{m_t^+-\Delta} x_{m_t^+} - \frac{\Delta}{\sigma}\mathbb{E}_{m_t^+-\Delta}\left(i_{m_t^+-\Delta} - \tilde{\pi}_{m_t^+} - \bar{i}\right) + \lambda_z z_{m_t^+-\Delta} - \lambda_a a_{m_t^+-\Delta},\\
\tilde{\pi}_{m_t^+-\Delta} &= \left(\frac{\beta}{1+\pi}\right)^{\Delta}\mathbb{E}_{m_t^+-\Delta}\tilde{\pi}_{m_t^+} + \kappa x_{m_t^+-\Delta},\\
i_{m_t^+-\Delta} &= \mathcal{D}\left(\tilde{\pi}_{m_t^+-\Delta}, x_{m_t^+-\Delta}, v_{m_t^-}\right).
\end{aligned}$$

Plugging the Phillips curve into the Taylor rule and the Taylor rule into the IS curve yields $x_{m_t^+-\Delta}$ as a function of itself only, given future variables and exogenous shocks:

$$\begin{aligned}
x_{m_t^+-\Delta} = \mathbb{E}_{m_t^+-\Delta} x_{m_t^+} - \frac{\Delta}{\sigma}\Bigg(&\mathcal{D}\left(\left(\frac{\beta}{1+\pi}\right)^{\Delta}\mathbb{E}_{m_t^+-\Delta}\tilde{\pi}_{m_t^+} + \kappa x_{m_t^+-\Delta}, x_{m_t^+-\Delta}, v_{m^-t}\right) - \mathbb{E}_{m_t^+-\Delta}\tilde{\pi}_{m_t^+} - \bar{i}\Bigg)\\
&+ \lambda_z z_{m_t^+-\Delta} - \lambda_a a_{m_t^+-\Delta}.
\end{aligned}$$

As the left-hand side of this equation is continuous in $x_{m_t^+-\Delta}$ but the right-hand side is discrete and features jumps, it has no solution in general.
If, instead, the index of the interest rate entering the IS curve is shifted one period ahead, the equation reads as

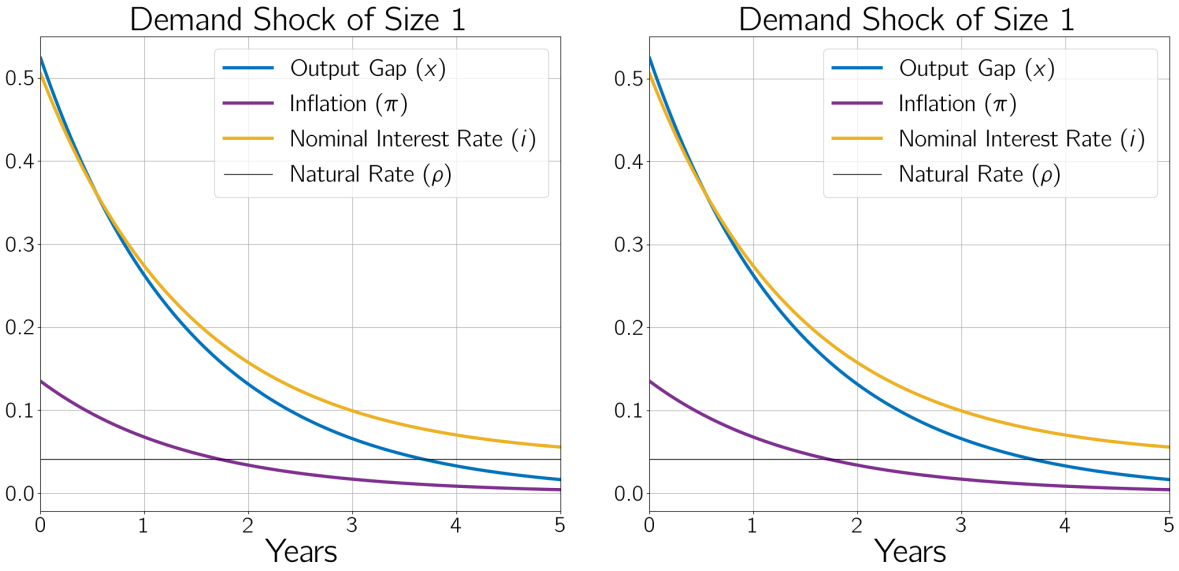
$$x_{m_t^+-\Delta} = \mathbb{E}_{m_t^+-\Delta} x_{m_t^+} - \frac{\Delta}{\sigma} \mathbb{E}_{m_t^+-\Delta} \left(\mathcal{D} \left(\left(\frac{\beta}{1+\pi} \right)^{\Delta} \tilde{\pi}_{m_t^{2+}} + \kappa x_{m_t^{2+}-\Delta}, x_{m_t^{2+}-\Delta}, v_{m_t^+} \right) - \tilde{\pi}_{m_t^+} - \bar{i} \right) + \lambda_z z_{m_t^+-\Delta} - \lambda_a a_{m_t^+-\Delta}. \tag{39}$$

Here, m_t^{2+} is introduced as a new notation and refers to the second central bank decision period in the future from the perspective of period t. Now, $x_{m_t^+-\Delta}$ appears on the left-hand side only, whereas the right-hand side comprises future variables (given when solving backward) and exogenous shocks.
To micro-found the index shift, one needs to specify the household budget constraint as done in (18). Here, I assume that a bond purchased in period $t-\Delta$ that matures in period t yields interest $(1+i_t)^{\Delta}$ instead of $(1+i_{t-\Delta})^{\Delta}$. This assumption seems valid particularly for floating-rate bonds with time-variant interest rates, or for bond-purchasing orders that are not immediately executed, given the period length of one day.
Quantitatively, the index shift does not make a visible difference if Δ is sufficiently small, as shown in Figure 14. Here, I plot the responses of two models to a size-one demand shock, once with the contemporaneous and once with the one-period-ahead time index used for the interest rate in the IS curve. Both models lack discrete characteristics of monetary policy, such that also the model without the index shift can be solved and the two responses can be compared.

E.2 Forward-Looking Taylor Rule

Monetary policy in the discrete model is based on inflation and the output gap in period $m_t^+-\Delta$, i.e., the last period before the next central bank meeting. Again, I show why this assumption is necessary to ensure the existence of the backward solution by supposing the contrary, namely that the Taylor rule is not forward-looking. In this case, the model in period m_t^- can be described as

$$\begin{aligned}
x_{m_t^-} &= \mathbb{E}_{m_t^-} x_{m_t^-+\Delta} - \frac{\Delta}{\sigma} \left(i_{m_t^-+\Delta} - \mathbb{E}_{m_t^-} \tilde{\pi}_{m_t^-+\Delta} - \bar{i} \right) + \lambda_z z_{m_t^-} - \lambda_a a_{m_t^-}, \\
\pi_{m_t^-} &= \left(\frac{\beta}{1+\pi} \right)^{\Delta} \mathbb{E}_{m_t^-} \tilde{\pi}_{m_t^-+\Delta} + \kappa x_{m_t^-}, \\
i_{m_t^-+\Delta} &= i_{m_t^-} = \mathcal{D} \left(\tilde{\pi}_{m_t^-}, x_{m_t^-}, v_{m_t^-} \right).
\end{aligned}$$



(a) IRF for model without index shift.

(b) IRF for model with index shift.

Figure 14: Effect of interest-rate index shift in the IS curve (4) on a demand-shock IRF. Calibration as given in Table 2, linear Taylor rule given by (6).

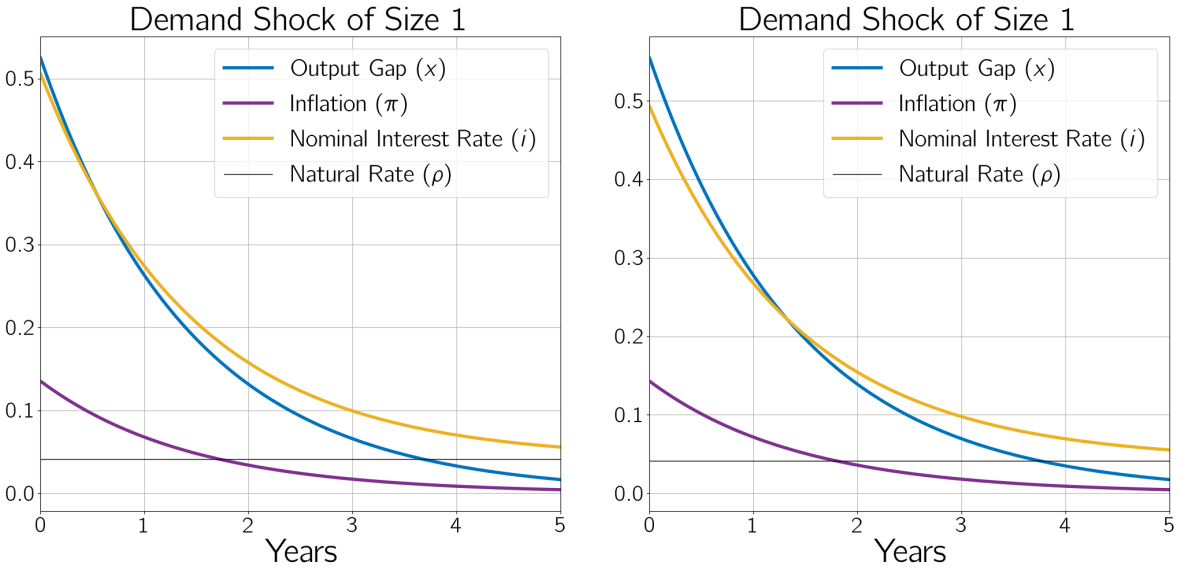
Thus, the Taylor rule determining the interest rate in period $t = m_t^-$ takes output and inflation in the same period as input arguments.
Combining all three equations yields

$$x_{m_t^-} = \mathbb{E}_{m_t^-} x_{m_t^- + \Delta} - \frac{\Delta}{\sigma}\left(\mathcal{D}\left(\left(\frac{\beta}{1+\pi}\right)^{\Delta} \mathbb{E}_{m_t^-}\tilde{\pi}_{m_t^-+\Delta} + \kappa x_{m_t^-}, x_{m_t^-}, v_{m_t^-}\right) - \mathbb{E}_{m_t^-}\tilde{\pi}_{m_t^-+\Delta} - \bar{i}\right) + \lambda_z z_{m_t^-} - \lambda_a a_{m_t^-}.$$

As in the previous subsection, this constitutes a fixed-point problem that, in general, has no solution as the equation's right-hand side is discrete and the left-hand side is continuous in $x_{m_t^-}$.
In contrast, such a fixed-point problem never emerges if the Taylor rule relates to the period before the next meeting. Then, for any period $t \in [m_t^-, m_t^+ - \Delta)$, one finds

$$x_t = \mathbb{E}_t x_{t+\Delta} - \frac{\Delta}{\sigma}\left(\mathcal{D}\left(\left(\frac{\beta}{1+\pi}\right)^{\Delta} \mathbb{E}_{m_t^-}\tilde{\pi}_{m_t^+} + \mathbb{E}_{m_t^-}\kappa x_{m_t^+-\Delta}, \mathbb{E}_{m_t^-} x_{m_t^+-\Delta}, v_{m_t^-}\right) - \mathbb{E}_t\tilde{\pi}_{t+\Delta} - \bar{i}\right) + \lambda_z z_t - \lambda_a a_t,$$

and $x_{m_t^+-\Delta}$ is given by (39).
Quantitatively, the forward-looking nature of the Taylor rule does affect the responses of the model to shocks visibly but not significantly, as depicted in Figure 15. Here, I compare the responses of two models to a demand shock. The Taylor rule in the model shown in Figure 15a reacts to output and inflation in the same period, whereas Figure 15b



(a) IRF with non-forward-looking Taylor rule. (b) IRF with forward-Looking Taylor rule.

Figure 15: Effect of a forward-looking Taylor rule on a demand-shock IRF. Calibration as given in Table 2.

is based on a linear Taylor rule that takes as input arguments expected variable values in period $t+\Delta\times\lfloor\mu_1/\Delta\rfloor-\Delta$ (i.e., $i_t=\ell(\mathbb{E}_t\pi_{t+\Delta\times\lfloor\mu_1/\Delta\rfloor-\Delta},\mathbb{E}_t x_{t+\Delta\times\lfloor\mu_1/\Delta\rfloor-\Delta},v_t)$. Thus, it is as forward-looking as the Taylor rule in the discrete model (14) in decision periods. The models underlying both figures do not feature any discrete components of monetary policy, such that the model without a forward-looking rule can be solved and both responses can be compared. As one would expect, the interest rate response is slightly less pronounced when the Taylor rule is forward-looking, as the expected values of the output gap and inflation in the future are smaller than the contemporaneous ones. In turn, this milder monetary policy response causes a stronger response of the output gap and inflation to the demand shock. All effects are quantitatively small.

F Forward Model Solution

To solve the model forward, consider its dynamics starting in period $m_t^- - \Delta$, i.e., the last period before a central bank decision period. As the period-$m_t^- - \Delta$ IS curve relates to $i_{m_t^-}$, the relevant interest rate will be given by the forward-looking rule $\mathcal{D}\left(\mathbb{E}_{m_t^-}\tilde{\pi}_{m_t^+-\Delta},\mathbb{E}_{m_t^-}x_{m_t^+-\Delta},v_{m_t^-}\right)$, such that the system can be written as

$$\begin{pmatrix} 1 & 0 \\ -\kappa & 1 \end{pmatrix} \begin{pmatrix} x_{m_t^- - \Delta} \\ \tilde{\pi}_{m_t^- - \Delta} \end{pmatrix} = \begin{pmatrix} 1 & \frac{\Delta}{\sigma} \\ 0 & \left(\frac{\beta}{1+\pi}\right)^{\Delta} \end{pmatrix} \begin{pmatrix} \mathbb{E}_{m_t^- - \Delta} x_{m_t^-} \\ \mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^-} \end{pmatrix} - \begin{pmatrix} -\lambda_z & \lambda_a \\ 0 & 0 \end{pmatrix} \begin{pmatrix} z_{m_t^- - \Delta} \\ a_{m_t^- - \Delta} \end{pmatrix}$$
$$- \begin{pmatrix} \frac{\Delta}{\sigma} \\ 0 \end{pmatrix} \left(\mathcal{D}\left(\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} v_{m_t^-} \right) - \bar{i} \right)$$

Define $y_{m_t^-} \equiv \begin{pmatrix} x_{m_t^-} \\ \tilde{\pi}_{m_t^-} \end{pmatrix}$, $u_{m_t^-} \equiv \begin{pmatrix} z_{m_t^-} \\ a_{m_t^-} \end{pmatrix}$, $B \equiv \begin{pmatrix} 1 & 0 \\ -\kappa & 1 \end{pmatrix}$, $A \equiv \begin{pmatrix} 1 & \frac{\Delta}{\sigma} \\ 0 & \left(\frac{\beta}{1+\pi}\right)^{\Delta} \end{pmatrix}$, $C \equiv \begin{pmatrix} \lambda_z & -\lambda_a \\ 0 & 0 \end{pmatrix}$, and $D \equiv \begin{pmatrix} \frac{\Delta}{\sigma} \\ 0 \end{pmatrix}$. Then, rearranging the system yields

$$\mathbb{E}_{m_t^- - \Delta} y_{m_t^-} = A^{-1} B y_{m_t^- - \Delta} + A^{-1} C u_{m_t^- - \Delta}$$
$$+ A^{-1} D \left(\mathcal{D}\left(\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} v_{m_t^-} \right) - \bar{i} \right). \tag{40}$$

Further, define $F \equiv \begin{pmatrix} \rho_z^{\Delta} & 0 \\ 0 & \rho_a^{\Delta} \end{pmatrix}$. Then, relying on the fact that the interest rate will remain constant at least until period $m_t^+ - \Delta$, one can iterate on (40) to find

$$\mathbb{E}_{m_t^- - \Delta} y_{m_t^- + (n-1)\Delta} = \left(A^{-1}B\right)^n y_{m_t^- - \Delta} + \sum_{k=1}^{n} \left(A^{-1}B\right)^{k-1} A^{-1} C F^{n-k} u_{m_t^- - \Delta}$$
$$+ \sum_{k=1}^{n} \left(A^{-1}B\right)^{k-1} A^{-1} D \left(\mathcal{D}\left(\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} v_{m_t^-} \right) - \bar{i} \right), \tag{41}$$

and thus

$$\mathbb{E}_{m_t^- - \Delta} y_{m_t^+ - \Delta} = \left(A^{-1}B\right)^{\left(m_t^+ - m_t^-\right)/\Delta} y_{m_t^- - \Delta} + \sum_{k=1}^{\left(m_t^+ - m_t^-\right)/\Delta} \left(A^{-1}B\right)^{k-1} A^{-1} C F^{\left(m_t^+ - m_t^-\right)/\Delta - k} u_{t_m - \Delta}$$
$$+ \sum_{k=1}^{\left(m_t^+ - m_t^-\right)/\Delta} \left(A^{-1}B\right)^{k-1} A^{-1} D \left(\mathcal{D}\left(\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} v_{m_t^-} \right) - \rho \right). \tag{42}$$

After using (42) to compute $\mathbb{E}_{m_t^- - \Delta} y_{m_t^+ - \Delta}$, one can shift the index of the equation and use $\mathbb{E}_{m_t^- - \Delta} y_{m_t^+ - \Delta}$ to determine $\mathbb{E}_{m_t^- - \Delta} y_{m_t^{2+} - \Delta}$, and so on. At the same time, given $\mathbb{E}_{m_t^- - \Delta} y_{m_t^+ - \Delta}$, (41) can be applied to solve for any period in between m_t^- and $m_t^+ - \Delta$, and all further periods between meetings. In the case $t_1 > 1$, a further equation is required to describe the dynamics between period 0 and period $t_1 - \Delta$. It is given by

$$\mathbb{E}_1 y_{n\Delta} = \left(A^{-1}B\right)^n y_1 + \sum_{k=1}^{n} \left(A^{-1}B\right)^{k-1} A^{-1} C F^{n-k} u_1 + \sum_{k=1}^{n} \left(A^{-1}B\right)^{k-1} A^{-1} D \left(i_0 - \bar{i}\right), \tag{43}$$

where i_0 denotes the initial interest rate. All in all, equations (41), (42), (43), and the

discrete Taylor rule (10) constitute the full forward solution for the model.
Note that applying (42) to solve the model forward requires the existence and uniqueness of its solution. Neither of the two is guaranteed. To show this, rewrite (42) as

$$\mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta} = c^x_{m_t^+ - \Delta} + D_1 \mathcal{D}\left(\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} v_{m_t^-}\right) \tag{44}$$

$$\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta} = c^\pi_{m_t^+ - \Delta} + D_2 \mathcal{D}\left(\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} v_{m_t^-}\right). \tag{45}$$

Here, $c^x_{m_t^+ - \Delta}$ and $c^\pi_{m_t^+ - \Delta}$ include all parts of the equations that are constant, exogenous, or relate to periods before $m_t^+ - \Delta$. D_1 and D_2 denote the upper and lower row of $\sum_{k=1}^{(m_t^+ - m_t^-)/\Delta} (A^{-1}B)^{k-1} A^{-1} D$, respectively.
Solving (44) for $\mathcal{D}\left(\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} v_{m_t^-}\right)$ and plugging the solution into (45) yields

$$\mathbb{E}_{m_t^- - \Delta} \tilde{\pi}_{m_t^+ - \Delta} = c^\pi_{m_t^+ - \Delta} - \frac{D_2}{D_1} c^x_{m_t^+ - \Delta} + \frac{D_2}{D_1} \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta},$$

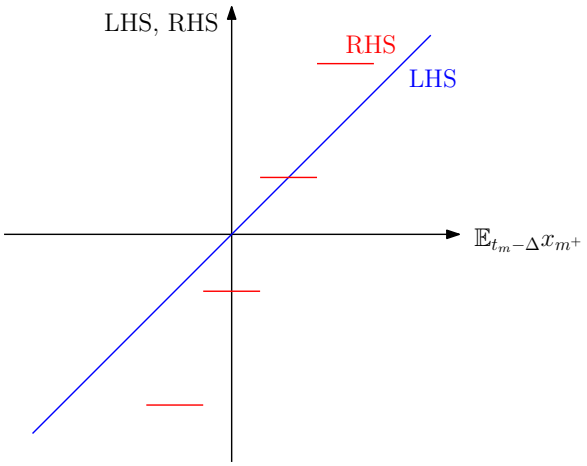
which can be used in (44) to find

$$\begin{aligned} \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta} = {} & c^x_{m_t^+ - \Delta} \\ & + D_1 \mathcal{D}\left(c^\pi_{m_t^+ - \Delta} - \frac{D_2}{D_1} c^x_{m_t^+ - \Delta} + \frac{D_2}{D_1} \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}, \mathbb{E}_{m_t^- - \Delta} v_{m_t^-}\right). \end{aligned} \tag{46}$$

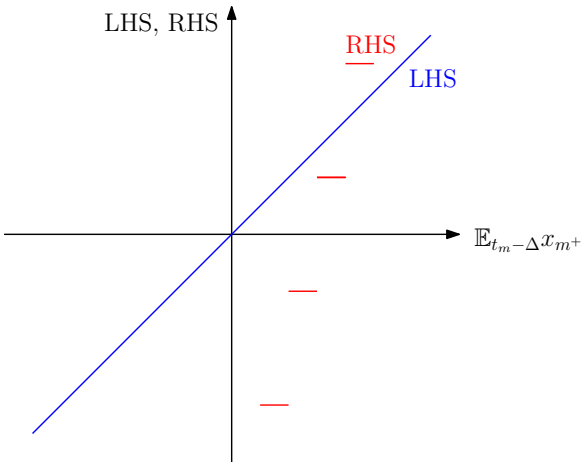
Thus, (46) constitutes a fixed-point problem in $\mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}$. As the discrete rule is the approximation of the linear rule (6) that is strictly increasing in all of its arguments, the right-hand side of this equation is either weakly increasing or weakly decreasing in $\mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}$, depending on D_1 and D_2. Given the discreteness of the interest rate rule, however, it is ex-ante unclear whether the fixed-point problem has zero, one, or multiple solutions, as exemplified in Figure 16.
It is a sufficient condition for (46) to have at most one solution if its right-hand side is weakly decreasing in $\mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}$ (see Panel 16d). Nevertheless, depending on $y_{m_t^- - \Delta}$ and shocks, which affect $c^x_{m_t^+ - \Delta}$ and $c^\pi_{m_t^+ - \Delta}$, the solution can be unique even for a weakly increasing right-hand side (see Figure 16a).
A sufficient condition for both the existence and uniqueness of the solution is that the right-hand side of (46) is constant in $\mathbb{E}_{m_t^- - \Delta} x_{m_t^+ - \Delta}$. Using (6), this requires

$$\frac{\phi_\pi}{\phi_x} = \frac{D_2}{D_1}.$$

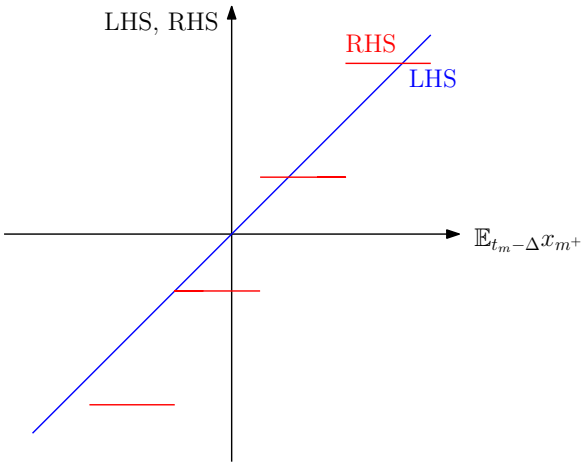
The standard calibration of the model as proposed by Galí (2015), however, implies $D_1 > 0$ and $D_2 < 0$, meaning that either ϕ_π or ϕ_x would need to be negative to meet this criterion.



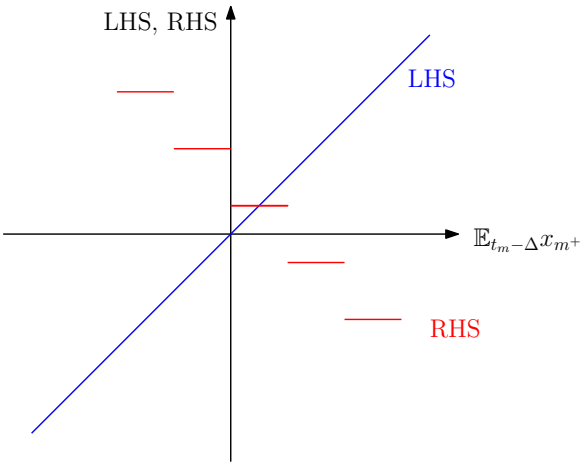
(a) Unique solution.



(b) No solution.



(c) Multiple solutions.



(d) A weakly decreasing right-hand Side rules out multiple solutions.

Figure 16: Different settings for the fixed-point problem in equation (46).

G Transformation of Quarterly Shock Processes Parameters

The parameter values presented in Section 5.1 governing shock processes were estimated based on quarterly data. However, the AR(1) processes determining shocks in the discrete model (7)–(9) are specified for a daily frequency, where ρ_i^{Δ} denotes daily persistence and ε_t^i the daily innovation for $i \in \{z, a, v\}$.

For the transformation of quarterly- into daily-frequency parameters, assume for simplicity that each quarter uniformly lasts Q days. Then, by iterating on the daily AR(1) process, the quarterly process can be written as a function of daily parameters and variables only. Consider the demand shock as an example:

$$\begin{aligned} z_t &= \rho_z^{\Delta} z_{t-\Delta} + \varepsilon_t^z \\ &= \rho_z^{2\Delta} z_{t-2\Delta} + \sum_{j=0}^{1} \rho_z^{j\Delta} \varepsilon_{t-j\Delta}^z \\ &= \rho_z^{Q\Delta} z_{t-Q\Delta} + \sum_{j=0}^{Q-1} \rho_z^{j\Delta} \varepsilon_{t-j\Delta}^z. \end{aligned}$$

In the quarterly model, the period length is then equal to $Q\Delta$, which equals $\frac{1}{4}$ as Δ is the period length of one quarter in terms of years. Thus, one obtains

$$\begin{aligned} \rho_z &= \left(\rho_z^q\right)^4, \\ \varepsilon_t^{z,q} &= \sum_{j=0}^{Q-1} \rho_z^{j\Delta} \varepsilon_{t-j\Delta}^z \end{aligned} \tag{47}$$

where ρ_z^q denotes the persistence and $\varepsilon_t^{z,q}$ the period-t residual of the quarterly demand shock process. Now, if the daily residual ε_t^z is i.i.d. with variance σ_z^2,

$$\begin{aligned} \operatorname{Var}\left(\varepsilon_t^{z,q}\right) &= \sigma_z^2 \sum_{j=0}^{Q-1} \rho_z^{2j\Delta} \\ &= \sigma_z^2 \frac{1-\rho_z^{2Q\Delta}}{1-\rho_z^{2\Delta}}. \end{aligned}$$

Denote the quarterly standard deviation of the residual by σ_z^q, and exploit $\rho_z^{Q\Delta} = \rho_z^{\frac{1}{4}}$ to obtain

$$\sigma_z = \sigma_z^q \sqrt{\frac{1-\rho_z^{2\Delta}}{1-\sqrt{\rho_z}}}. \tag{48}$$

Thus, parameters for the discrete model can be backed out from estimates based on quarterly-frequency data using (47) and (48).

H Robustness Analysis for the Simulated Business Cycle

In Section 5, a simulated business cycle was analyzed by decomposing all variables' variance into a systematic, discreteness, and infrequency component. Innovations underlying the simulation were drawn for a specific seed (seed 1) using Python's numpy.random module. In Table 7, I show that the results presented in Table 4 do not significantly change when shocks are drawn for five further seeds.

Table 7: Robustness of variance decomposition results derived in Table 4 for multiple seeds.

		Share of Variance Explained by Component (%)			
Seed	**Variable**	**Discreteness**	**Infrequency**	**Systematic**	**Total**
1 (benchmark)	Interest Rate	-0.80	0.19	100.61	100.00
	Output Gap	1.95	-1.47	99.53	100.00
	Inflation	-2.36	-2.11	104.47	100.00
2	Interest Rate	-0.77	-0.18	100.95	100.00
	Output Gap	1.78	-1.58	99.80	100.00
	Inflation	-1.96	-2.07	104.03	100.00
3	Interest Rate	-0.87	0.08	100.80	100.00
	Output Gap	2.02	-1.62	99.61	100.00
	Inflation	-2.47	-2.14	104.61	100.00
4	Interest Rate	-1.38	0.96	100.43	100.00
	Output Gap	2.41	-1.31	98.90	100.00
	Inflation	-3.23	-2.09	105.32	100.00
5	Interest Rate	-0.70	0.16	100.54	100.00
	Output Gap	1.90	-1.36	99.46	100.00
	Inflation	-2.05	-2.05	104.10	100.00
6	Interest Rate	-0.95	0.66	100.29	100.00
	Output Gap	2.23	-1.45	99.22	100.00
	Inflation	-2.72	-2.11	104.84	100.00

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