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Government Debt Maturity in Japan: 1965 to the Present*

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Abstract

This study constructs a dataset of Japanese government bonds' maturity structure for the fiscal years 1965–2020. Using the maturity structure data at the end of each fiscal year for the past three decades, this study structurally estimates a canonical preferred-habitat term structure model extracting the bond supply factor. The results provide a debt maturity equation in the fiscal-year cycle and demonstrate that two yield factors (bond supply factor and short-term interest rate) can account for annual-frequency variations in Japanese bond yields. The supply factor also explains the continued decline in the long-term interest rate for the past two decades.

JEL Classification: E43, E52, G11, G12, H63

Keywords: maturity structure, yield curve, debt management, Japan, supply factor, bond yield

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Government debt has been expanding in the prevailing environment of low interest–rates environment worldwide. Japan is an outstanding case of soaring government debt, with the ratio of government debt to gross domestic product (GDP) increasing from over 60 percent to well-over 200 percent in the past three decades. The ratio of maturity-weighted debt to GDP, which is often used as a proxy for the bond supply factor, has continued to increase in Japan while interest rates have fallen (Figure 1). Does this "conundrum" indicate that a positive relationship between the supply factor and bond yields as discussed by, for example, Krishnamurthy and Vissing-Jorgensen (2012) and Greenwood and Vayanos (2014), does not hold for Japan? Alternatively, should a different measure for the supply factor be used? We argue for the latter using a term structure framework.

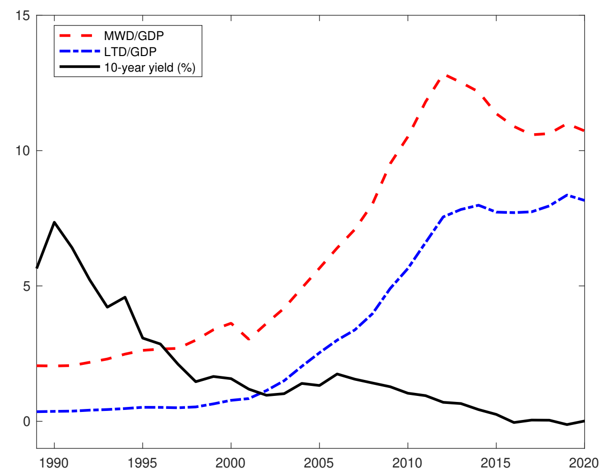


Figure 1: Maturity-weighted debt to gross domestic product and bond yields in Japan
Notes: This figure plots the ratio of maturity-weighted debt to GDP in Japan following Greenwood and Vayanos(2014). MWD/GDP and LTD/GDP stand for the ratio of maturity weighted debt to GDP and the ratio of long-term debt to GDP respectively. The Bank of Japan's government bond holdings are excluded from this debt. The 10-year bond yield is zero coupon yield (also shown in Figure 4).

Moving away from Ricardian equivalence (Barro, 1974), the term structure literature has started to analyze the effects of the bond supply and maturity structure of government bonds on bond yields. Vayanos and Vila (2021) develop a no-arbitrage term structure model with preferred habitat investors and arbitrageurs. Greenwood and Vayanos (2014) present a special case of Vayanos and Vila (2021) assuming that the demand and supply for each maturity in the absence of arbitrageurs are price inelastic, thereby downplaying the role of preferred–habitat investors in absorbing supply shocks from the government. These authors then provide empirical support for their model for the United States (US) by regressing bond yields on the ratio of maturity-weighted debt to GDP, their proxy for the supply factor. Hayashi (2018) provides an algorithm to solve a discrete version of Greenwood and Vayanos (2014) allowing for many supply factors. Hamilton and Wu (2012) estimate a discrete version of Vayanos and Vila (2021),[1] assuming the preferred–habitat investors' bond demand is a decreasing affine function of the yield, and thus, at equilibrium, the supply factor is an affine function of the level, slope, and curvature factors. As a result, a bond supply shock is a combination of three-factor shocks that may be difficult to identify.

More recently, additional studies identify bond demand or supply shocks based on the preferred habitat theory formalized by Vayanos and Vila (2021). The theoretical model has been extended by introducing the effective lower bound on nominal rates (King, 2019*b*)[2] and incorporating macroeconomic variables (King, 2019*a*). Gorodnichenko and Ray (2017) identify bond demand shocks by high-frequency changes in futures prices before and after each treasury auction, exploiting the primary market structure in the US. These authors then examine how shocks spread to other maturities. Kaminska and Zinna (2020) propose and estimate a state-space representation of Vayanos and Vila (2021) on the term structure of real rates in which the US bond supply factor is a linear function of selected observed supply factors, that is, reserves by foreign officials, large-scale bond purchases by the Fed, and Treasury supply. The authors note that these supply factors better capture the low-frequency behavior of the supply factor. This study extracts the bond supply factor exploiting the bond maturity structure information at an annual frequency in Japan and structurally estimates

[1] Fukunaga, Kato and Koeda (2015) and Koeda (2017) estimate a discrete version of Hamilton and Wu (2012) for Japan.

[2] This study does not introduce the zero lower bound (ZLB) or the effective lower bound (ELB), because bond yields often took negative values in Japan, and did so even before the introduction of a negative interest rate policy in early 2016; and thus, bond yields were not necessarily bounded by the short rate's ELB in Japan.

a discrete version of the Greenwood and Vayanos (2014) model. The structural estimation enables us to identify the supply shock and its effect on bond yields without worrying about the endogeneity addressed by Greenwood and Vayanos (2014) using instrumental variable estimation. To the best of our knowledge, no previous study in the literature has estimated the bond supply factor directly using maturity structure information besides the ratio of maturity-weighted debt to GDP. Furthermore, the evolution of the government debt maturity structure has not been fully analyzed for many countries.

To fill these research gaps for the case of Japan, this study constructs and analyzes a maturity structure database for Japanese government bonds (JGBs) and bills. Japan is an interesting case to study because it developed the world's second-largest government bond market (OECD, 2019). Additionally, and data on issue-level government bond characteristics (e.g., coupon and maturity) have been available since fiscal year (FY) 1965 when the post-World War II (WWII) de facto debt management policy in Japan started. Moreover, the country actively implements a debt maturity policy. The Ministry of Finance (MOF) announces a detailed debt maturity plan when the budget for the upcoming fiscal year is approved by the Cabinet in December, several months before the new FY begins in April. Furthermore, the Bank of Japan (BOJ), the largest government bondholder currently, influences the maturity structure of marketable bonds through its asset purchases under quantitative easing. The pre-announced debt maturity plan includes which specific bond maturities to issue and by how much. Thus, the plan is more detailed than those of other countries. For example, in the United Kingdom, the issuance plan categorizes bond maturities into three types: short, medium, and long term. In the US, the issuance plan is revised every six months. In Japan, based on the plan, government bonds are issued through "communications with the markets" until the maturity structure is finalized at the fiscal-year end. To analyze the maturity structure consistently with the FY cycle, we construct the maturity structure of marketable bonds at the fiscal-year end (end-March), which is free from noises reflecting temporary changes and adjustments in the maturity structure within the year.

The constructed maturity structure variable is used for model estimation via the maximum likelihood method.

This study makes several contributions. First, it proposes a novel way to extract the supply factor, which resolves the conundrum that interest rates are seemingly negatively correlated with the bond supply factor. While the existing supply proxy, maturity–weighted debt to GDP, prefixes the loading on debt in each maturity with increasing weights, the loading of our supply factor has a higher weight on 2–10 year remaining maturities than other maturities, particularly 6–8 year remaining maturities possibly reflecting a close link with the futures markets. Furthermore, our supply factor declined for the past three decades despite the continued expansion of the ratio of government debt to GDP. We find that this decline accounts for the continued fall in the long-term interest rate in the two-decade long zero lower bound (ZLB) interest rate environment. Second, this study is the first to construct maturity structure data for Japan using issue-level data since FY1965. Thus, the data help us understand how debt management policy has evolved from the aspects of maturity structure. Third, the structural estimation enables us to identify the supply shock and its effect on bond yields without worrying about they endogeneity addressed by Greenwood and Vayanos (2014) using instrumental variable estimation. Further, it enables us to link the supply factor to the maturity structure, which clarifies a debt maturity policy function.

The rest of the paper is organized as follows. Section I documents the maturity structure data construction and discusses the evolution of the structure. Section II presents the model. Section III explains the estimation strategy and results. Section IV conducts an impulse response exercise. Section V provides an additional discussion. Section VI concludes.

I Maturity Structure and Debt Management Policy

This section explains our maturity structure data construction and documents how these variables have evolved in changing debt management policies in Japan.

A Maturity structure data

JGBs are debt securities issued by the central government of Japan. This study constructs maturity structure data with annual frequency at the end of the FY (the Japanese FY starts in April and ends in March). Our sample begins from March 1966 (end of FY1965) and ends in March 2021 (end of FY2020).

As in Fukunaga, Kato and Koeda (2015),[3] we collected data from the Japanese Bond Handbook (Ko-Shasai Binran) on every JGB issued. The handbook is published semiannually (end-March and end-September) by the Japan Securities Dealers Association (JSDA). The handbook provides data on the bond characteristics of each bond, including bond type, series number, issue date, coupon rate, maturity, direct underwriter (if any), and semi-annual observations of face value outstanding. Outstanding marketable JGBs reflect changes due to buybacks, liquidity operations, and early redemption. Since the JSDA stopped publishing this information after March 2019, the last two years of the sample period were constructed by combining publicly available data on JGBs and T-bill issuance and bond holdings by the BOJ. We provide a detailed description of the data construction in the Online Appendix. We break the stream of each bond's cash flows into principal and coupon payments to construct the future cash flows, as in Greenwood and Vayanos (2014).[4]

We group JGBs[5] and T-bills into marketable and non-marketable types.[6] The non-marketable bonds include the following:

- Bonds underwritten by the Trust Fund Bureau (TFB), Postal Savings, and Postal Life Insurance or Pension Reserves;

[3]However, there are several differences (i) our definitions of non-marketable bonds differ, and (ii) we use a cash flow based calculation rather than a principal based one.

[4]We apply a principal based calculation for inflation-indexed bonds and flexible interest rate bonds.

[5]Officially, JGBs are government bonds issued with maturity of one year or longer.

[6]Legally, JGBs can be categorized into three types: (i) general bonds, (ii) Fiscal Investment and Loan Program (FILP) bonds, and (iii) other bonds (MoF, 2004). General bonds are to be repaid by tax revenues. FILP bonds provide funding for government investment and lending operations under the FILP and are to be repaid by returns from FILP operations. Other bonds include subsidy, subscription, and contribution bonds. The marketable general and FILP bonds are treated as the same financial instruments in the JGB markets.

- JGBs for individual investors[7]; and

- Other small amounts (i.e., subsidy, subscription, and contribution bonds).

Figure 2 shows outstanding marketable and non-marketable JGBs in trillion yen. Outstanding non-marketable JGB is shown by the difference between the blue dashed and green dash-dotted lines. In early years of the investigated period, non-marketable bonds were mostly those underwritten by the TFB. The TFB is a branch of the MOF that manages funds collected by the government through postal savings, pensions and other systems in JGBs. It became active in FY1965 and was later abolished in FY2001. Bonds underwritten by postal savings, postal life insurance, and pension reserves increased particularly amid the reform of the Fiscal Loan Fund Special Account in the 2000s.[8] Since FY2013, the BOJ's purchases of long-term bonds have reduced the size of marketable bonds, excluding BOJ holdings (black solid line in Figure 2).

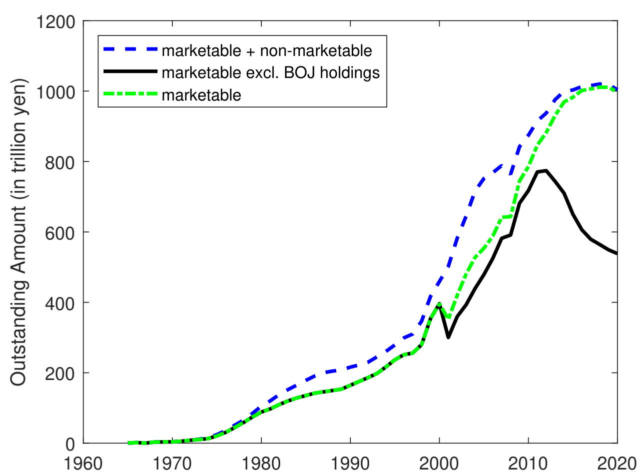
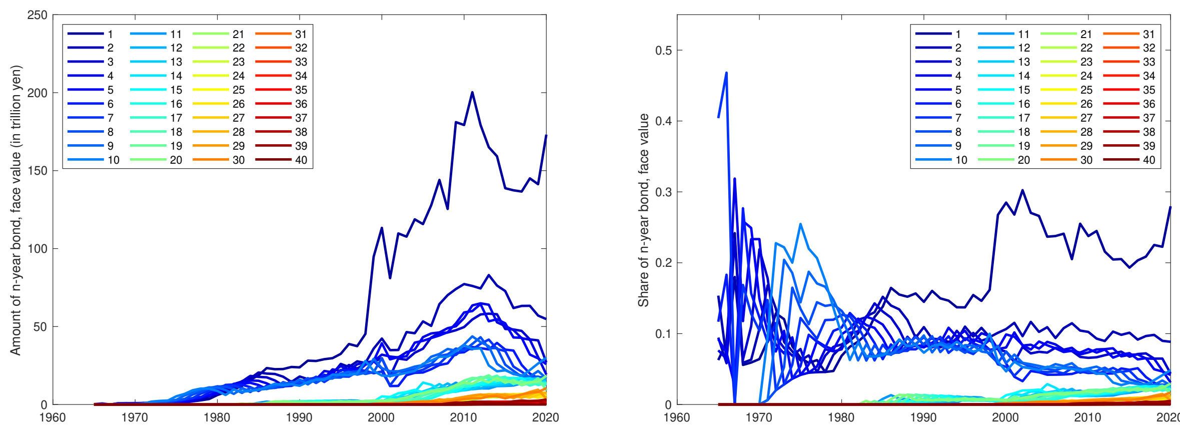


Figure 2: Marketable vs. non-marketable Japanese government bonds, FY1965-2020
Notes: This figure plots the face-value outstanding of marketable bonds (green dash-dotted line), marketable bonds excluding BOJ holdings (black solid line), and marketable bonds plus non-marketable bonds (blue dashed line) in trillion Japanese yen.

[7]JGBs for individual investors were established in 2003 to diversify JGB products.
[8]For more discussion, see for example, Cargill and Yoshino (2003).

The net face-value of the bond outstanding with remaining maturity greater than $n-1$ years and less than or equal to n years ($S^n_{FV,t}$) is shown in Figure 3a. "Net" means the net bond supply by the government (i.e., MOF issuance subtracting the BOJ holdings) constructed by aggregating cash flows across individual bonds. The nominal share of the n-year bond supplied, $s^n_{FV,t}$ for $n = 1, ..., N$, is defined as $S^n_{FV,t}/\sum_i S^i_{FV,t}$ where N is the maximum maturity in years. The denominator ($\sum_i S^i_{FV,t}$) is the total net face-value of bonds supplied by the government in period t, which corresponds to the black solid line in Figure 2. By construction, $s^n_{FV,t}$ adds up to one over N-year maturities. Figure 3b plots $s^n_{FV,t}$ with $N = 40$. We discuss the evolution of $s^n_{FV,t}$ and the related debt management policy changes[9] in the next subsection.



(a) Bonds outstanding by maturity ($S^n_{FV,t}$, in trillion yen) (b) The share of bond supply by maturity ($s^n_{FV,t}$)

Figure 3: Maturity structure

Notes: Figure 3a plots bonds outstanding by maturity in trillion yen and Figure 3b plots the bond-supply share. FV in the subscript of $s^n_{FV,t}$ stands for "face value."

[9] Koeda (2021) reviews the related literature on Japanese debt management policies (most of them are written in Japanese) and presents the following four phases of the debt management policy: Phase I (FY1965–1975, early market development); Phase II (FY1976–1998, stabilizing the maturity structure); Phase III (FY1999–2012, further market developments); and Phase IV (FY2013–2020, increased BOJ long-term bond purchases).

B The evolution of debt management policy

The post-WWII debt management policy in Japan de facto started in FY1965. In that year, JGBs were issued for the first time after the war under a supplementary budget to cover a revenue shortfall . In the early years of the investigated period, the share of bond supply $s^n_{FV,t}$ (Figure 3b) was unstable, as there was only one type of bond (7-years). Syndication underwriting was the only issuance method for marketable JGBs, and the secondary markets were underdeveloped (Section 1.1, MoF, 2004).[10] In the late 1970s, the market became thicker (Figure 3a) and the maturity structure gradually stabilized (Figure 3b). The development of the secondary market and the diversification of bond type gained more policy attention (Sections 1.1 and 2.2, MoF, 2004). Amid financial liberalization and internationalization, there were notable market developments, such as the introduction of an auction in 1978, the opening of the futures markets in 1986, and the introduction of a "partial" auction system for 10-year bonds in 1989 by Syndicate, the main underwriting body at that time. In 1999, the auction was introduced for a 1-year financial bill, and the market size notably increased for bonds and bills with remaining maturity of 1 year or less (Figure 3a). The resulting shorting of the maturity possibly reflects the introduction of BOJ's zero interest rate policy (McCauley and Ueda, 2012). "Communications with the markets" (the phrase repeated used by the MOF) gained more importance and the TBF was finally abolished in 2001. Furthermore, after the end of the syndication underwriting system in 2006 in response to some market participants' views that the system became outdated and lacked market efficiency (pp. 207–209, MoF, 2012), the auction method became the only issuance method of marketable JGBs. Since April 2013, the BOJ has been purchasing bonds with long maturity under its qualitative and quantitative easing policy with an explicit target on the average maturity of its bond holdings. In September 2016, the BOJ introduced a yield curve control targeting a10-year JGB yield of around 0 percent by committing to necessary

[10] Syndication underwriting was participated by the most of financial institutions, and the underwritten bonds were usually bought and held until maturity (p. 7 and p. 132, MoF, 2012).

JGB purchases. As a result, the marketable bonds outstanding excluding BOJ holdings has notably declined since FY2013 (Figure 2).

II Model

The model is a discrete version of Greenwood and Vayanos (2014), which has a setting that allows us to focus on the effect of government bond supply on bond yields and risks. In the model, bond supply changes affect bond yields by changing the amount of interest-rate risk held by arbitrageurs. There are bonds with different maturities in the economy. Demand and supply for each maturity in the absence of arbitrageurs are assumed to be price inelastic.

As in Hamilton and Wu (2012) and Hayashi (2018), in our model, the decision problem of arbitrageurs is to maximize the risk-adjusted portfolio return subject to an adding-up constraint. The maximization problem of arbitrageurs is

$$\max_{\{z_t^n\}_{n=1}^N} \left[\mathrm{E}_t\left(R_{t+1}\right) - \frac{\gamma}{2}\mathrm{Var}_t\left(R_{t+1}\right) \right] \quad \text{subject to} \quad \sum_{n=1}^{N} z_t^n = 1, \tag{1}$$

where z_t^n is the nominal share of arbitrageurs' n-period bond holdings, γ captures the degree of risk aversion, and N is the maximum maturity that arbitrageurs hold. The holding–period return on arbitrageurs' portfolio (R_{t+1}) is defined by

$$R_{t+1} \equiv \sum_{n=1}^{N} \frac{P_{t+1}^{(n-1)} - P_t^{(n)}}{P_t^{(n)}} z_t^n. \tag{2}$$

Accordingly, the first-order condition is derived as follows:

$$\mathrm{E}_t\left[\frac{P_{t+1}^{(n-1)} - P_t^{(n)}}{P_t^{(n)}} \right] - \frac{1 - P_t^{(1)}}{P_t^{(1)}} = \gamma \frac{1}{2} \frac{\partial \mathrm{Var}_t\left(R_{t+1}\right)}{\partial z_t^n}, \; n = 2, 3, \ldots, N. \tag{3}$$

A Factor dynamics

The vector of state variables X consists of the supply factor (β) and the short rate (r),

$$X_t = \begin{bmatrix} \beta_t \\ r_t \end{bmatrix},$$

It is assumed to follow a Gaussian VAR(1):

$$X_{t+1} = \boldsymbol{\mu} + \boldsymbol{\rho} X_t + \Sigma \boldsymbol{\varepsilon}_{t+1},\ \boldsymbol{\varepsilon}_t \sim N(0, I), \tag{4}$$

where

$$\boldsymbol{\mu} = \begin{bmatrix} \mu_\beta \\ \mu_r \end{bmatrix}, \boldsymbol{\rho} = \begin{bmatrix} \rho_\beta & 0 \\ \rho_{r\beta} & \rho_{rr} \end{bmatrix}, \Sigma = \begin{bmatrix} \sigma_\beta & 0 \\ 0 & \sigma_r \end{bmatrix}, \boldsymbol{\varepsilon}_t = \begin{bmatrix} \varepsilon_t^\beta \\ \varepsilon_t^r \end{bmatrix}.$$

Thus, the supply factor dynamics is assumed to be unaffected by the short rate (as assumed by Greenwood and Vayanos, 2014), and the short rate is assumed to be unaffected by contemporaneous supply shocks. This implies that the central bank can control the short rate in the short run regardless of the contemporaneous maturity structure for $n = 2, 3, \ldots, N$.[11]

This implies that the short rate r depends on its lag and the lagged vector of the supply factor, as follows:

$$r_t = \mu_r + [\rho_{r\beta}, \rho_{rr}] X_{t-1} + \sigma_r \varepsilon_t^r. \tag{5}$$

B Maturity structure

As in Greenwood and Vayanos (2014), the share of the net bond supply with maturity n relative to the total net bond supply at time t (s_t^n) is described as a factor model. The net bond supply is defined by the bond outstanding in the government bond markets subtracting bonds held by private preferred habitat investors. The net bond supply is an affine function of the vector of supply factors β_t so that the maturity structure equation is given by

[11] Greenwood and Vayanos (2014) mainly focus on the case where the supply factor and the short rate are independent $\rho_{r\beta} = \sigma_{r\beta} = 0$.

$$s_t^n = \kappa_n + \psi_n \beta_t, \tag{6}$$

where $\sum_{n=1}^{N} s_t^n = 1$.

C Equilibrium term structure

The bond market clears for all maturities at the equilibrium. The market-clearing condition is defined by $z_t^n = s_t^n$. In equilibrium, the n-period log bond price can be expressed as

$$p_t^n = \bar{a}_n + \bar{\mathbf{b}}_n^{'} X_t,$$

where

$$\bar{\mathbf{b}}_n' = \bar{\mathbf{b}}_{n-1}'\boldsymbol{\rho} - \gamma\bar{\mathbf{b}}_{n-1}'\mathbf{\Sigma\Sigma}' \begin{bmatrix} \bar{\mathbf{b}}_1 & \bar{\mathbf{b}}_2 & \cdots & \bar{\mathbf{b}}_{N-1} \end{bmatrix} \widetilde{\boldsymbol{\Psi}}_N + \bar{\mathbf{b}}_1', \tag{7}$$

$$\bar{a}_n = \bar{a}_{n-1} + \bar{\mathbf{b}}_{n-1}'\boldsymbol{\mu} + \frac{1}{2}\bar{\mathbf{b}}_{n-1}'\mathbf{\Sigma\Sigma}'\bar{\mathbf{b}}_{n-1} - \gamma\bar{\mathbf{b}}_{n-1}'\mathbf{\Sigma\Sigma}' \begin{bmatrix} \bar{\mathbf{b}}_1 & \bar{\mathbf{b}}_2 & \cdots & \bar{\mathbf{b}}_{N-1} \end{bmatrix} \boldsymbol{\kappa}_N + \bar{a}_1, \tag{8}$$

where

$$\boldsymbol{\kappa}_{\bar{N}} = \begin{bmatrix} \kappa_2 \\ \vdots \\ \kappa_N \end{bmatrix}, \quad \boldsymbol{\Psi}_N = \begin{bmatrix} \psi_2 \\ \vdots \\ \psi_N \end{bmatrix}, \quad \tilde{\boldsymbol{\Psi}}_N = \begin{bmatrix} \boldsymbol{\Psi}_N, & \mathbf{0} \end{bmatrix}. \tag{9}$$

Thus, the n-period log bond yield is given by

$$r_t^n = a_n + \boldsymbol{b}_n^{'} X_t, \tag{10}$$

$a_n = -\bar{a}_n/n$ and $\boldsymbol{b}_n = -\bar{\boldsymbol{b}}_n/n$. The appendix provides the derivation of Eqs. (7) and (8).

III Estimation

This section describes the data used in the estimation and estimation strategy, and presents the results. Given the data availability of bond yields, the sample period starts from the end of FY1989 and ends at the end of FY2020 (end-March). Despite the short sample size of 32 years, we estimate the model based on annual frequency for the following reasons. First, this study analyzes the debt maturity policy consistent with the fiscal-year cycle. Higher-frequency maturity structure data help increase the sample size while containing noise reflecting temporary changes and adjustments in the maturity structure within the year. Second, we exploit cross-sectional information in addition to time-series information in our estimation. In the benchmark estimation, we use cross sectional information on 20 maturity-structure variables and 20 bond yield variables. Thus we use 1280 data points in total, which may be sufficient. We discuss the implied small sample behavior in Section V.

A Data

To estimate the model, we need annual data on (i) bond yields with different maturities and (ii) the maturity structure of the net bond supply in the market value. For (i), we use the FY averages of the end-of-month Bloomberg's zero yield curve data from FY1989 to FY2020,[12] as presented in Figure 4, using the bond yields of 1, 2, .., 20-year maturities (denoted as $R_t^1, R_t^2, ..., R_t^{20}$) for the estimation. Thus, $N = 20$. Table .1 in the appendix provides summary statistics on the bond yields and maturities.

For (ii), we compute the maturity structure variable in the market values defined by $s_t^n = (P_t^n S_{FV,t}^n - H_t^n)/\sum_i (P_t^i S_{FV,t}^i - H_t^i)$, where P_t^n is the n-year bond price implied by the end of FY yield curve information and $S_{FV,t}^n$ is the net face-value of bond supply as defined in Subsection 2.1. H_t^n is the private preferred-habitat investors' demand on n-year bond in the market value.

Since full data on H_t^n are unavailable, we compute H_t^n based on recent disclosure information on life insurance companies.[13] Our analysis focuses on life insurance companies because

[12]Bloomberg's zero coupon bond yield data are available from April 1989. We apply Nelson–Siegel curves to zero-coupon yields obtained from Bloomberg to obtain bond yield for all maturities.

[13]As Fukunaga, Kato and Koeda (2015) indicate, insurance business law in Japan requires every insurance company to disclose the amount outstanding of JGBs and T-bills by remaining maturity at least once each business year. The amount of bond holding by insurance companies is reported mostly in the face value under the "held to maturity" purpose applying the amortized cost method. The disclosure information usually reports the end of fiscal year values.

they already hold three quarters of the JGBs held by insurance companies, according to the BOJ's flow-of-funds data[14]. We denote their bond holdings by the specific range of maturities over i years and less than or equal to j years as $H_{i<\tau\leq j}$, where τ is the remaining maturity in years. In the annual reports of life insurance companies, the remaining maturities are grouped by "1 year or less," "over 1 year and less than or equal to 3 years," "over 3 years and less than or equal to 5 years," "over 5 years and less than or equal to 7 years," "over 7 years and less than or equal to 10 years," and "over 10 years." Thus, there are six maturity groups. We construct an unbalanced panel data on JGB holdings by maturity for about 40 life insurance companies in Japan for 2016-2019 (37, 39, 39, 40 companies respectively). The share of life insurance companies' holdings in the total net bond supply in the six maturity groups are 2, 5, 8, 18, 28, 48 percent on average respectively. The share in each maturity year (h_t^n) is determined via cubic Hermite interpolation of the average years of each maturity group and the corresponding shares[15]. We use these shares to compute H_t^n where $H_t^n{=}h_t^n P_t^n S_{FV,t}^n$.

[14] The flows-of-fund data provided by the BOJ show that over 20 % of the volume of government bonds and bills is held by private insurance companies and pension funds. These private preferred-habitat investors, especially life insurance companies, increased their holdings of JGBs with maturities over 10 years to match the duration of assets to the long duration of their liabilities under regulations and accounting standards that force them to reduce their risky asset holdings.

[15] Specifically, we choose 0.5, 2, 4, 6, 8.5, 15, 20 and 30 years for the average years and 0.02, 0.05, 0.08, 0.18, 0.28, 0.48, 0.48, and 0.48 for the shares in the benchmark estimation.

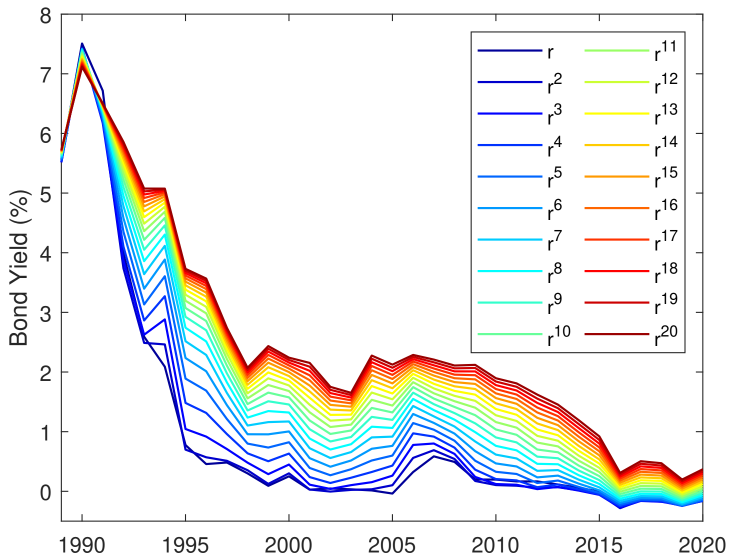


Figure 4: Bond yield data

Notes: This figure plots Japanese bond yields with different maturities in annualized rate in percent.

B State space representation and estimation strategy

The model can be rewritten in a state space representation. The transition equations of the latent state variables $X_t = [\beta_t, r_t]$' are given by

$$X_{t+1} = \boldsymbol{\rho} X_t + \Sigma \boldsymbol{\varepsilon}_{t+1},\ \boldsymbol{\varepsilon}_t \sim N(0, I), \tag{11}$$

where the constant term is zero for identification.[16] The measurement equations consist of the short-rate equation, the yield equations and the maturity-structure equations given as follows.

Short rate equation:

$$R_t^1 = \delta + [0, 1]X_t, \tag{12}$$

[16]The values of s_t^n are unchanged with different nonzero values of $\boldsymbol{\mu}$ as the values of $\boldsymbol{\kappa}$ and $\boldsymbol{\Psi}$ can adjust accordingly. The same argument holds for the values of r_t^n.

Yield equations:

$$\begin{bmatrix} R_t^2 \\ \vdots \\ R_t^N \end{bmatrix} = \begin{bmatrix} a_2 \\ \vdots \\ a_N \end{bmatrix} + \begin{bmatrix} \boldsymbol{b}_2^{'} \\ \vdots \\ \boldsymbol{b}_N^{'} \end{bmatrix} X_t + \sigma^R \boldsymbol{u}_t^R,\ \boldsymbol{u}_t^R \sim N(0, I_{N-1}), \tag{13}$$

Maturity-structure equations:

$$\begin{bmatrix} s_t^2 \\ \vdots \\ s_t^N \end{bmatrix} = \begin{bmatrix} \kappa_2 \\ \vdots \\ \kappa_N \end{bmatrix} + \begin{bmatrix} [\psi_2, 0] \\ \vdots \\ [\psi_N, 0] \end{bmatrix} X_t + \sigma^s \boldsymbol{u}_t^s,\ \boldsymbol{u}_t^s \sim N(0, I_{N-1}), \tag{14}$$

where $\boldsymbol{u}_t^R$ and $\boldsymbol{u}_t^s$ are measurement errors in the yield- and maturity-structure equations respectively. We estimate the model using the maximum likelihood method with Kalman filtering. The model parameters are $\Theta = [\delta, \boldsymbol{\rho}, \Sigma, \boldsymbol{\kappa}, \boldsymbol{\Psi}, \gamma, \sigma^R, \sigma^s]$. Standard errors are derived by numerically computing the Hessian matrix.

C Estimated results

Figure 5 shows the estimated state variables in the model. The short rate (r, black-dashed line) drops in the early 1990s and stays very low thereafter. The supply factor (β, red-solid line), the factor that governs the maturity structure, turns negative in the mid-1990s and has been declining for the past three decades pushing down yield curves persistently despite the continued expansion of maturity-weighted debt to GDP.

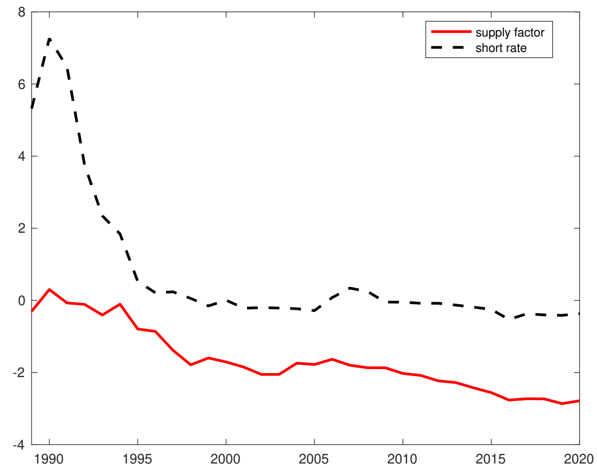


Figure 5: The estimated state variables (β and r)
Notes: This figure plots the estimate β (red solid line) and r (black dashed line).

Table 1 reports the estimated model parameters. Standard errors are shown in parentheses. Despite the low-frequency data, the supply factor dynamics is very persistent with ρ_β at about 0.97. An increase in supply raises expected future short rates with a positive $\rho_{r\beta}$. The maturity structure equation coefficients $\boldsymbol{\kappa}$ and $\boldsymbol{\Psi}$ are plotted in Figure 6. The coefficients $\boldsymbol{\kappa}$ capture the average maturity structure and the coefficients $\boldsymbol{\Psi}$ captures systemic debt management.[17] The bond supply shares of 2-10 year remaining maturities $(\psi_2, ..., \psi_{10})$ are estimated to be positive, implying that a decrease in the supply factor involves a fall in the shares of 2-10 year remaining maturities.

[17]Vayanos and Vila (2021) assume a smoothed function for $\boldsymbol{\Psi}$ which converges to zero as the maturity increases. Our estimated $\boldsymbol{\Psi}$, if smoothed, can be approximated with their assumed function.

Maturity Structure						Factor Dynamics		
κ_2	0.1920	(0.0044)	ψ_2	0.0013	(0.0020)	ρ_β	0.9742	(0.0111)
κ_3	0.1138	(0.0041)	ψ_3	0.0119	(0.0043)	$\rho_{r\beta}$	0.4219	(0.1314)
κ_4	0.1109	(0.0057)	ψ_4	0.0105	(0.0052)	ρ_{rr}	0.7820	(0.0440)
κ_5	0.0958	(0.0033)	ψ_5	0.0073	(0.0038)	Σ_{11}	0.1061	(0.0329)
κ_6	0.0842	(0.0042)	ψ_6	0.0167	(0.0042)	Σ_{22}	0.4092	(0.0710)
κ_7	0.0752	(0.0029)	ψ_7	0.0144	(0.0049)			
κ_8	0.0712	(0.0023)	ψ_8	0.0129	(0.0043)	Short Rate		
κ_9	0.0660	(0.0036)	ψ_9	0.0113	(0.0041)	δ	0.2455	(0.0472)
κ_{10}	0.0561	(0.0023)	ψ_{10}	0.0084	(0.0034)			
κ_{11}	0.0027	(0.0007)	ψ_{11}	-0.0041	(0.0016)	Risk Aversion		
κ_{12}	0.0028	(0.0007)	ψ_{12}	-0.0038	(0.0015)	γ	3.7696	(0.4538)
κ_{13}	0.0036	(0.0008)	ψ_{13}	-0.0033	(0.0014)			
κ_{14}	0.0043	(0.0009)	ψ_{14}	-0.0030	(0.0014)	Measurement Errors		
κ_{15}	0.0047	(0.0010)	ψ_{15}	-0.0027	(0.0013)	σ_ε	0.1074	(0.0089)
κ_{16}	0.0047	(0.0012)	ψ_{16}	-0.0019	(0.0012)	σ_s	0.0072	(0.0006)
κ_{17}	0.0055	(0.0015)	ψ_{17}	-0.0016	(0.0015)			
κ_{18}	0.0060	(0.0017)	ψ_{18}	-0.0014	(0.0013)			
κ_{19}	0.0063	(0.0018)	ψ_{19}	-0.0014	(0.0014)			
κ_{20}	0.0060	(0.0016)	ψ_{20}	-0.0015	(0.0013)			

Table 1: Estimated parameters

Notes: The table shows the estimated coefficients and standard errors in parentheses.

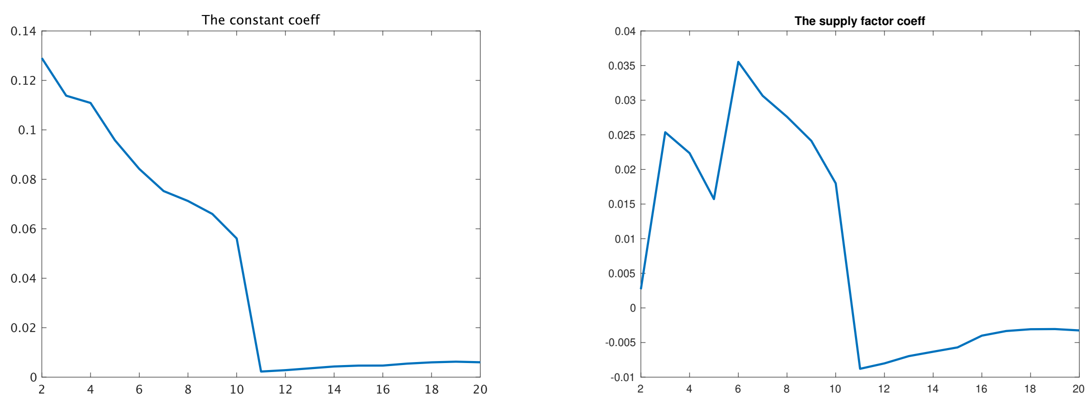


Figure 6: Estimated maturity structure

Notes: The estimated $\boldsymbol{\kappa}_N$ and $\boldsymbol{\Psi}_N$ in the maturity structure equation (Eq. (6)) are plotted against maturity.

Figure 7 shows the estimated yield-curve coefficients, that is, a_n and $\boldsymbol{b}_n$ in Eq. (10). Consistent with Greenwood and Vayanos (2014), the estimated coefficient of supply in the yield equation is increasing with maturity (Figure 7, left). It is worth noting that the shape of this factor loading looks like that of the slope factor. The supply coefficient in the model-implied expected one-period holding period return (i.e., $E_t(p_{t+1}^n) - p_t^{n+1}$) is computed as the first element of $\bar{\mathbf{b}}_n\boldsymbol{\rho} - \bar{\mathbf{b}}_{n+1}$ or equivalently the first element of $(n+1)\boldsymbol{b}_{n+1} - n\boldsymbol{b}_n\boldsymbol{\rho}$. The value of this coefficient, which captures how much the expected return changes in response to one-unit change in the supply factor change (ceteris paribus), is estimated to increase against maturity, as shown in Figure 8.

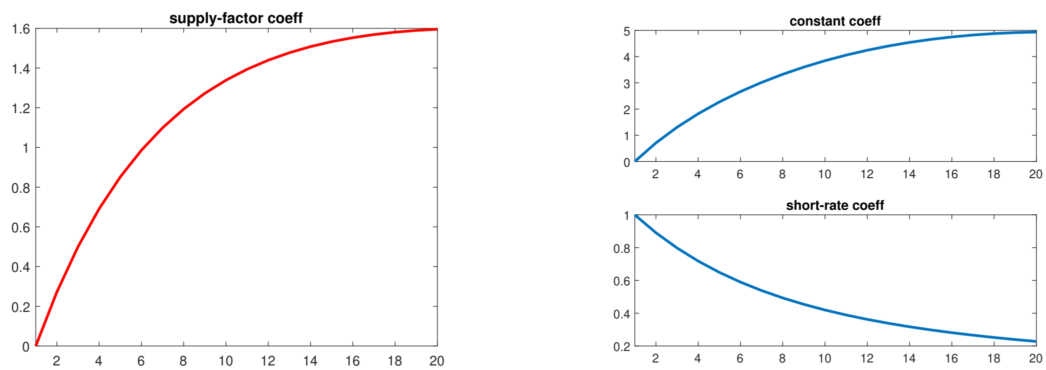


Figure 7: Estimated yield-equation coefficients
Notes: These figures plot the yield-equation coefficients. The left figure corresponds to the supply-factor coefficient; the top right figure corresponds to the constant coefficient; and the bottom right figure corresponds to the short-rate coefficient.

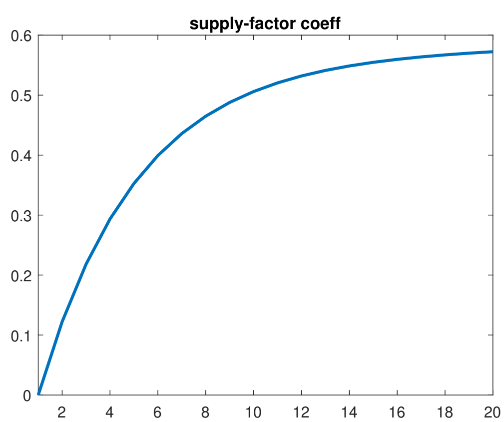


Figure 8: Estimated supply coefficient in the return equation
Notes: This figure plots the supply coefficient in the return equation against maturity.

The model-implied yield decomposes into the contributions from each factor, as shown in Figure 9. The figure shows how the short rate and the supply factor explain the 10-year bond fluctuations. The black solid line shows the actual 10-year bond yield minus the constant term in the yield equation (a_{10}), and the red bars show the supply factor term in the yield equation (the first element of $\bar{\mathbf{b}}'_{10}X_t$). The blue bars show the short-rate term in the yield equation (the second element of $\bar{\mathbf{b}}'_{10}X_t$). The supply factor term in the yield equation captures the duration effect highlighted by Greenwood and Vayanos (2014). A more negative supply factor accounts for the continued decline in the long-term bond yields under a ZLB environment, while the short rate is stacked near the ZLB.

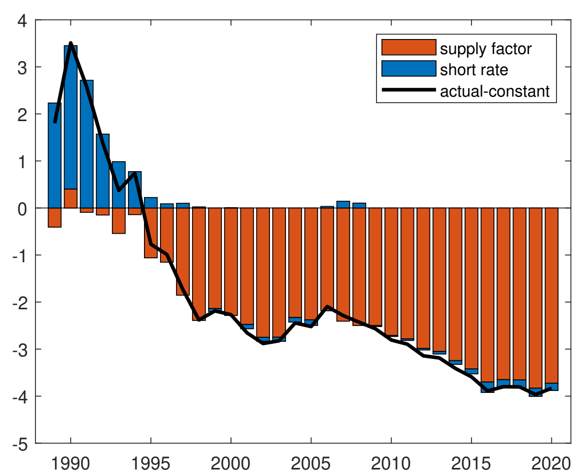


Figure 9: Decomposing the model-implied 10-year yield
Notes: This figure plots the estimated short-rate and supply-factor terms (blue and red bars, respectively) and the actual 10-year bond yield minus the estimated constant term (black solid line) in Eq. (10).

IV Impulse Responses to the Supply Shock

How do bond yields and the maturity structure respond to a supply shock? The impulse response of a model-implied variable from the term structure model, y_t to a yield-factor shock can be defined by the difference between the following conditional expectations:

$$E_t\left[y_{t+k} \mid X_t + \nu_t; \Theta\right] - E_t\left[y_{t+k} \mid X_t; \Theta\right], \tag{15}$$

where ν_t represents the vector of shocks. As in Diebold, Rudebusch and Aruoba (2006), the yield-curve factors are treated as the endogenous variables in the VAR estimation. We numerically compute Eq. (15) given the model parameter estimates. The error bands are obtained by drawing parameter vectors from the asymptotic distribution and picking the 84th and 16th percentiles.[18]

Figure 10 shows the impulse responses of the model-implied variables to a positive supply shock that increases the supply factor by 1 upon impact (note that 1 standard deviation of the estimated β is about 0.9). It is expected to take nearly a decade for the effect on the supply factor to be halved, as the supply factor is persistent. The model-implied 10-year bond yield jumps up by about 135 basis points upon impact, with large risk of further interest hikes. The short rate is likely to increase. One caveat regarding this impulse response exercise is that it assumes the shock is fully absorbed by arbitrageurs. If the shock were fully absorbed by preferred-habitat investors, there would be no change in the maturity structure of the net bond supply that arbitrageurs face in the model.

V Discussion

A Are private preferred-habitat investors price elastic?

One important model assumption is that preferred-habitat investors are assumed to be price inelastic, as in Greenwood and Vayanos (2014). We investigate this assumption's validity via a simple regression analysis using the panel data for life-insurance companies (see Subsection A for data construction). Table 2 reports the firm-fixed effect regression of the log of their

[18]See Hayashi and Koeda (2019) for an application.

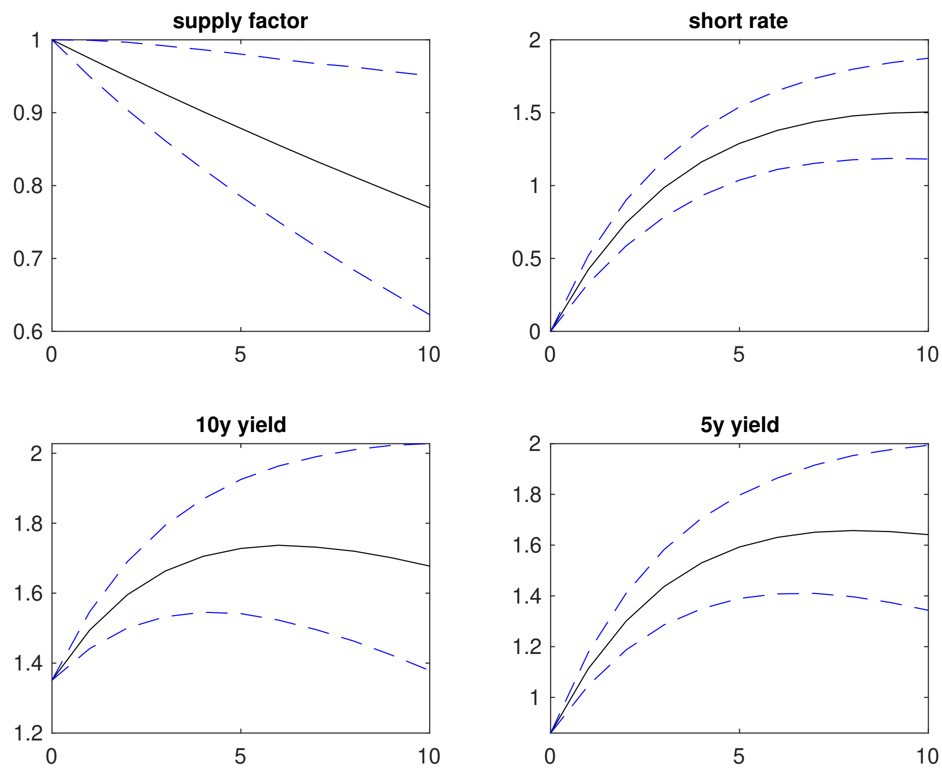


Figure 10: Impulse responses to a supply shock

Notes: This figure plots the impulse responses of the supply factor (top left), short rate (top right, annualized rate in percent), 10-year yield (bottom left, annualized rate in percent), and 5-year yield (bottom right, annualized rate in percent).

bond holdings by specific range of maturities ($logH_{i<\tau\leq j}$) on the average of bond yields over the corresponding maturity range ($r_{i<\tau\leq j}$), where τ is the remaining maturity in years. The estimated results show that all the coefficients were statistically insignificant, not rejecting the model assumption that the private preferred-habitat investors are price inelastic in Japan.

Dependent Variable:	$\log H_{\tau\leq 1}$	$\log H_{1<\tau\leq 3}$	$\log H_{3<\tau\leq 5}$	$\log H_{5<\tau\leq 7}$	$\log H_{7<\tau\leq 10}$	$\log H_{10<\tau}$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
r	-0.026						
	(1.454)						
$r_{1<\tau\leq 3}$		-0.007					
		(1.669)					
$r_{3<\tau\leq 5}$			-1.001				
			(1.478)				
$r_{5<\tau\leq 7}$				1.181			
				(0.914)			
$r_{7<\tau\leq 10}$					-0.518		
					(0.635)		
r_{10}						-0.135	
						(0.355)	
r_{20}							-0.024
							(0.176)
Observations	111	121	122	124	130	139	139
Adj. R^2	0.854	0.844	0.833	0.886	0.945	0.989	0.989

Table 2: Demand Elasticity of Life Insurance Companies

Notes: The table regresses life insurance companies' bond holdings for specific maturities on the corresponding bond yields. All specifications use firm fixed effects. Standard errors are shown in parentheses.

B Is there an appropriate proxy for the supply factor?

Our supply factor presented in the previous section is a latent variable. However, for the supply factor, some may prefer to explicitly use a proxy that does not require model estimation. One natural candidate for such a proxy is the first principal component obtained by applying the principal component analysis (PCA) to the shares of the net bond supply by maturity. The PCA-based supply proxy chooses the loading to capture variations in the maturity structure, whereas the existing supply proxy, maturity-weighted debt to GDP, prefixes the loading on debt in each maturity with increasing weights. Figure 11 plots the PCA-based supply proxy in the face value and in the market value denoted as $\hat{\beta}_{FV}$ and $\hat{\beta}_{MV}$ respectively. The corresponding PCA score is standardized for easier interpretation of the results. In the case of $N = 20$, $\hat{\beta}_{FV}$ and $\hat{\beta}_{MV}$ explain 72% and 68% of the variations in the corresponding maturity structure variables.[19] Figure 11 shows that the PCA-based supply factor declined

[19] Specifically, $\hat{\beta}_{FV}$ and $\hat{\beta}_{MV}$ are the first principal components obtained by applying the PCA to $s^1_{FV}, ..., s^{20}_{FV}$ and $s^1, ..., s^{20}$,respectively.

for the past three decades despite the continued expansion of the ratio of government debt to GDP. Thus, the declining PCA-based supply factor is theoretically consistent with the fall in the long-term interest rate in Japan. We also find that the PCA-based loading has a higher weight on 6-10 year remaining maturities than other maturities, possibly reflecting a close link with futures markets.

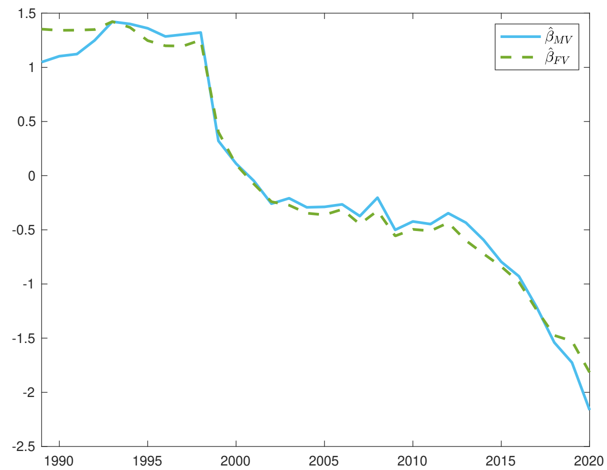


Figure 11: PCA-based supply factor

Notes: This figure plots the first principal component analysis (PCA) component obtained by applying the PCA on s_t^n for $n = 1, ..., N$.

Panel A : Maturity-weighted debt to GDP						
Dependent variable:	r^{10}					
Estimator:	OLS			2SLS		
	(1)	(2)	(3)	(4)	(5)	(6)
MWD/GDP	-0.158	-0.058	-0.047	-0.146	-0.050	-0.032
	(0.120)	(0.033)	(0.0531)	(0.081)	(0.031)	(0.026)
$\hat{\beta}_{MV}$		0.563			0.586	
		(0.192)			(0.157)	
$\hat{\beta}_{FV}$			0.642			0.691
			(0.213)			(0.160)
r	0.747	0.691	0.656	0.759	0.705	0.671
	(0.081)	(0.046)	(0.059)	(0.080)	(0.049)	(0.057)
Constant	2.210	1.616	1.578	2.120	1.559	1.483
	(0.731)	(0.278)	(0.263)	(0.654)	(0.290)	(0.249)
Observations	32	32	32	32	31	31
Adj. R^2	0.944	0.969	0.968	0.943	0.966	0.965
Panel B: Long-term debt to GDP						
Dependent variable:	r^{10}					
	OLS			2SLS		
	(7)	(8)	(9)	(10)	(11)	(12)
LTD/GDP	-0.201	-0.082	-0.072	-0.195	-0.084	-0.057
	(0.074)	(0.055)	(0.056)	(0.087)	(0.068)	(0.046)
$\hat{\beta}_{MV}$		0.516			0.508	
		(0.255)			(0.257)	
$\hat{\beta}_{FV}$			0.586			0.629
			(0.272)			(0.194)
r	0.757	0.702	0.668	0.761	0.715	0.680
	(0.069)	(0.047)	(0.062)	(0.079)	(0.049)	(0.057)
Constant	1.880	1.516	1.514	1.855	1.520	1.463
	(0.469)	(0.239)	(0.242)	(0.538)	(0.345)	(0.248)
Observations	32	32	32	32	31	31
Adj. R^2	0.953	0.969	0.969	0.953	0.966	0.966

Table 3: Bond Yields and Supply-Factor Proxies

Notes: The table regresses 10-year bond yields on the variables of interest, the supply factor and the short rate using our annual data from FY1989 to FY2020. The variable of interest is an alternative supply factor measure, where MWD/GDP stands for the fraction of maturity weighted debt to GDP and LTD/GDP stands for the fraction of long-term debt to GDP. We use two supply factors: $\hat{\beta}_{MV}$ stands for the supply factor computed using maturity structure based on market value, and $\hat{\beta}_{MV}$ stands for the supply factor based on face value. OLS stands for ordinary least squares. The two stage least squares (2SLS) estimation columns show the estimation results from second-stage regressions. We instrument for the alternative supply factors by the ratio of debt-to-GDP, D/GDP, and for $\hat{\beta}$ by lagged $\hat{\beta}$. Both the first- and second-stage regressions include the short-rate as a control. Newey–West standard errors with 1-year lag are shown in parentheses.

Dependent variable:	r^{10}					
Estimator:		OLS			2SLS	
	(1)	(2)	(3)	(4)	(5)	(6)
D/GDP	-1.322	-0.381	-0.241	-1.467	-0.565	-0.431
	(1.101)	(0.216)	(0.188)	(1.399)	(0.298)	(0.256)
$\hat{\beta}_{MV}$		0.633			0.575	
		(0.139)			(0.134)	
$\hat{\beta}_{FV}$			0.725			0.658
			(0.162)			(0.159)
r	0.746	0.683	0.647	0.746	0.690	0.661
	(0.078)	(0.048)	(0.058)	(0.077)	(0.052)	(0.060)
Constant	2.386	1.593	1.502	2.534	1.765	1.675
	(0.770)	(0.259)	(0.238)	(0.883)	(0.314)	(0.292)
Observations	32	32	32	31	31	31
Adj. R^2	0.926	0.967	0.967	0.917	0.963	0.963

Table 4: Size versus Composition

Notes: The table regresses 10-year bond yields on the variables of interest, the supply factor and the short rate using our annual data from FY1989 to FY2020. The variable of interest is a debt to GDP, D/GDP. We use two supply factors: $\hat{\beta}_{MV}$ stands for supply factor computed using maturity structure based on market value and $\hat{\beta}_{FV}$ stands for supply factor based on face value. The columns of 2SLS estimation show the estimation results from second-stage regressions. We instrument for the debt-to-GDP by the lagged debt-to-GDP, D/GDP, and for $\hat{\beta}$ by lagged $\hat{\beta}$. Both the first- and second-stage regressions include the short-rate as a control. Newey-West standard errors with 1-year lag are shown in parentheses.

To examine how well our supply proxies ($\hat{\beta}_{FV}$ and $\hat{\beta}_{MV}$) accounts for bond yield fluctuations compared with the existing proxies, we conduct a simple model-free regression of a 10-year bond yield on $\hat{\beta}_{FV}$ and $\hat{\beta}_{MV}$ and an existing supply proxy controlling for the short rate. Table 3 includes MWD/GDP or LTD/GDP as the existing proxies, and shows that $\hat{\beta}_{FV}$ or $\hat{\beta}_{MV}$ outstandingly explains the 10-year bond yield fluctuations. Since $\hat{\beta}_{FV}$ or $\hat{\beta}_{MV}$ is a linear function of the shares of bond supply by maturity, it captures the composition of government debt. Table 4 adds the size of government debt, specifically, total face-value bonds outstanding to GDP (D/GDP) as the additional supply measure. The estimated results show that the coefficient for $\hat{\beta}_{FV}$ or $\hat{\beta}_{MV}$ was statistically significantly positive, whereas the coefficient for D/GDP is statistically insignificant. Thus only the composition effect is confirmed in the regression. Going forward, however, increasing the size of the outstanding JGBs while keeping the same maturity structure may significantly impact bond yields, particularly in light of the shrinking absorbing capacity of JGBs (Hoshi and Ito (2014)).

C Short sample simulations

To examine the implied small sample behavior of the model coefficients, we used the estimated model to generate 10,000 samples of the same length as our sample period (31 observations) using a similar approach to that applied by Ang, Piazzesi and Wei (2006). In each simulated sample, we re-estimated the model via maximum likelihood. We find that none of the simulation results suggested that the yield curve coefficient regarding the supply factor is negative, thereby supporting Proposition 1 in Greenwood and Vayanos (2014). We also examine the small sample distributions of ρ_β from the re-estimated model. The population coefficient from the estimated model ("truth") is 0.97. The average and median coefficients across all the simulations from re-estimating the model are both around 0.97, thus they were reasonably close to the truth, with standard deviations of the coefficients across the simulations of 0.02.

VI Conclusions

Using the constructed maturity structure data, we analyzed the evolution of the maturity structure for JGB markets over the past five decades. We also structurally estimated a bond supply factor that focuses on the composition rather than the size of the outstanding JGB for the past three decades. We concluded that the composition of government debt explains the continued fall in nominal long-term interest rates in Japan, and thus, Japanese government debt management plays an important role in managing a low-interest rate environment.

The structural estimation results indicated that the supply-factor effect on bond yields is significant. In particular, despite the continued expansion of the ratio of government debt to GDP, the estimated supply factor has been declining, pushing down the long-term bond yields. This decline has accompanied a notable increase in the share of bond remaining maturities of less than 1 year and also a decrease in the share of bond remaining maturities between 2 and 10 years. The impulse response exercise implies that a positive supply shock, if it occurs, could persistently raise bond yields, heightening risks in JGB markets that have a large rollover size of about 20 percent of GDP each year. The supply factor shock may have been reflecting various events, such as the development of money markets, the BOJ's long-term government bond purchases, and the maturity diversification of issuance policy. In future research, it would be worthwhile to further analyze the circumstances and policies that drive supply factors to change.

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Appendix

Appendix Tables and Figures

Variable	Mean	SD	Min	Median	Max
Bond Yield (%)					
r	1.011	2.039	-0.282	0.181	7.507
r^2	0.998	1.984	-0.282	0.115	7.431
r^3	1.087	1.975	-0.271	0.252	7.417
r^4	1.214	1.982	-0.251	0.397	7.419
r^5	1.351	1.990	-0.242	0.558	7.420
r^6	1.486	1.996	-0.228	0.738	7.417
r^7	1.614	1.998	-0.208	0.910	7.407
r^8	1.731	1.996	-0.183	1.073	7.393
r^9	1.839	1.991	-0.153	1.223	7.374
r^{10}	1.937	1.982	-0.122	1.360	7.352
Supply Factor					
$\hat{\beta}_{MV}$	0.000	1.000	-2.164	-0.262	1.422
$\hat{\beta}_{FV}$	0.000	1.000	-1.817	-0.317	1.422
MWD/GDP	6.518	3.994	2.044	5.290	12.833
LTD/GDP	3.513	3.209	0.354	2.280	8.357
Maturity Structure					
s^1	0.212	0.050	0.137	0.212	0.302
s^2	0.100	0.008	0.088	0.098	0.117
s^3	0.077	0.013	0.044	0.075	0.104
s^4	0.080	0.015	0.031	0.080	0.108
s^5	0.077	0.013	0.042	0.078	0.099
s^6	0.057	0.022	0.027	0.047	0.096
s^7	0.056	0.020	0.027	0.050	0.096
s^8	0.058	0.020	0.027	0.052	0.096
s^9	0.059	0.020	0.027	0.057	0.098
s^{10}	0.0567	0.020	0.027	0.051	0.100
Other Variables					
D/GDP	0.910	0.436	0.349	0.879	1.664
Inflation	0.516	1.192	-1.700	0.200	3.300

Table .1: Summary Statistics

Notes: The table shows the summary statistics of our data. Our sample is 32 years with cross-sectional information on the different maturities of bond yields and maturity structure. Bond yields are zero coupon rates obtained from Bloomberg. The maturity structure variable s^n is the shares of bonds with remaining maturity less than or equal to n years but greater than $n-1$ years divided by the total net value of bonds for all government bonds. Supply factor $\hat{\beta}$ is the first principal component derived from the maturity structure variables. The maturity-weighted debt to GDP ratio, MWD/GDP, and the long-term debt to GDP ratio, LTD/GDP, are computed following Greenwood and Vayanos (2014) and Krishnamurthy and Vissing-Jorgensen (2012), respectively.

Panel A: OLS				
Dependent Variable:	r^{10}			
	(1)	(2)	(3)	(4)
Inflation Rate (π)	1.020	-0.229	-0.1767	-0.149
	(0.496)	(0.126)	(0.034)	(0.036)
r		1.006	0.775	0.721
		(0.111)	(0.050)	(0.060)
$\hat{\beta}_{MV}$			0.726	
			(0.146)	
$\hat{\beta}_{FV}$				0.786
				(0.133)
Constant	1.412	1.039	1.240	1.286
	(0.497)	(0.496)	(0.128)	(0.130)
Observations	32	32	32	32
Adj. R^2	0.355	0.875	0.969	0.970

Panel B: 2SLS				
Dependent Variable:	r^{10}			
	(5)	(6)	(7)	(8)
Inflation Rate (π)	1.739	-0.682	-0.543	-0.594
	(0.412)	(0.545)	(0.441)	(0.429)
r		1.203	0.948	0.938
		(0.188)	(0.140)	(0.149)
$\hat{\beta}_{MV}$			0.680	
			(0.133)	
$\hat{\beta}_{FV}$				0.709
				(0.134)
Constant	1.055	1.078	1.260	1.299
	(0.562)	(0.321)	(0.147)	(0.162)
Observations	31	31	31	31
Adj. R^2	0.052	0.816	0.935	0.923

Table .2: Bond Yield, Inflation Rate and Supply Factors

Notes: The table regresses 10-year bond yield on the variables of interest, the inflation rate, supply factor, the short rate using our annual data from FY1989 to FY2020. We use two supply factors: $\hat{\beta}_{MV}$ stands for supply factor computed using maturity structure based on market value and $\hat{\beta}_{MV}$ stands for supply factor based on face value. The columns of 2SLS estimation show the estimation results from second-stage regressions. We instrument for the inflation rate by the lagged inflation rate and for $\hat{\beta}$ by lagged $\hat{\beta}$. Both the first- and second-stage regressions for columns 2-4 and 6-8 include the short-rate as a control. Newey-West standard errors with 1-year lag are shown in parentheses.

Derivation of factor-loadings equations

The FOCs for n-period bonds are

$$E_t\left[\frac{P_{t+1}^{n-1}-P_t^n}{P_t^n}\right]-\frac{1-P_t^1}{P_t^1}=\gamma\frac{1}{2}\frac{\partial \mathrm{Var}\left(R_{t+1}\right)}{\partial z_t^n}.$$

Although the left-hand side is approximated by the same form as Eq. (A1.3) of Hayashi (2018), the right-hand side is slightly different because of the constant term in maturity structure equations:

$$S_{N,t}=\boldsymbol{\kappa}_N+\boldsymbol{\Psi}_N\beta_t=\boldsymbol{\kappa}_N+\widetilde{\boldsymbol{\Psi}}_N X_t$$

Assume

$$\log P_t^{(n)}=\bar{a}_n+\bar{\mathbf{b}}_n' X_t$$

$$\begin{aligned}
E_t\left[\frac{P_{t+1}^{(n-1)}-P_t^{(n)}}{P_t^{(n)}}\right] &= E_t\left[\exp\left(\log P_{t+1}^{(n-1)}-\log P_t^{(n)}\right)\right]-1\\
&\approx E_t\left(\log P_{t+1}^{(n-1)}-\log P_t^{(n)}\right)+\frac{1}{2}Var_t\left(\log P_{t+1}^{(n-1)}-\log P_t^{(n)}\right)\\
&= E_t\left(\bar{a}_{n-1}+\bar{\mathbf{b}}_{n-1}'X_{t+1}-\bar{a}_n+\bar{\mathbf{b}}_n'X_t\right)+\frac{1}{2}Var\left(\bar{a}_{n-1}+\bar{\mathbf{b}}_{n-1}'X_{t+1}-\bar{a}_n+\bar{\mathbf{b}}_n'X_t\right)\\
&= \bar{a}_{n-1}+\bar{\mathbf{b}}_{n-1}'\left(\mu+\rho X_t\right)-\bar{a}_n+\bar{\mathbf{b}}_n'X_t+\frac{1}{2}Var\left(\bar{\mathbf{b}}_{n-1}'\Sigma\varepsilon_{t+1}\right)\\
&= \bar{a}_{n-1}+\bar{\mathbf{b}}_{n-1}'\mu-\bar{a}_n+\left(\bar{\mathbf{b}}_{n-1}'\rho+\bar{\mathbf{b}}_n'\right)X_t+\frac{1}{2}\bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\bar{\mathbf{b}}_{n-1}
\end{aligned}$$

where $\Omega=\Sigma\Sigma'$. The second term of the left-hand side is approximated by

$$\frac{1-P_t^{(1)}}{P_t^{(1)}}\approx-\log P_t^{(1)}=\bar{a}_1+\bar{\mathbf{b}}_1'X_t.$$

Thus, the left-hand side becomes

$$E_t\left[\frac{P_{t+1}^{(n-1)}-P_t^{(n)}}{P_t^{(n)}}\right]-\frac{1-P_t^{(1)}}{P_t^{(1)}}=\bar{a}_{n-1}+\bar{\mathbf{b}}_{n-1}^{'}\mu-\bar{a}_n+\left(\bar{\mathbf{b}}_{n-1}^{'}\rho+\bar{\mathbf{b}}_n^{'}\right)X_t+\frac{1}{2}\bar{\mathbf{b}}_{n-1}^{'}\mathbf{\Sigma\Sigma}'\bar{\mathbf{b}}_{n-1}-\bar{a}_1+\bar{\mathbf{b}}_1^{'}X_t$$

$$=\left(\bar{a}_{n-1}+\bar{\mathbf{b}}_{n-1}^{\prime}\boldsymbol{\mu}-\bar{a}_n+\frac{1}{2}\bar{\mathbf{b}}_{n-1}^{\prime}\mathbf{\Sigma\Sigma}'\bar{\mathbf{b}}_{n-1}+\bar{a}_1\right)+\left(\bar{\mathbf{b}}_{n-1}^{\prime}\boldsymbol{\rho}-\bar{\mathbf{b}}_n^{\prime}+\bar{\mathbf{b}}_1^{\prime}\right)X_t.$$

Next, we approximate the portfolio return to derive the variance in the right-hand side as follows:

$$\begin{aligned}
R_{t+1} &\equiv \sum_{n=1}^{\bar{N}}\frac{P_{t+1}^{(n-1)}-P_t^{(n)}}{P_t^{(n)}}z_t^n \approx \sum_{n=1}^{N}\left(\log P_{t+1}^{(n-1)}-\log P_t^n\right)z_t^n \\
&= -\log P_t^{(1)}z_t^1+\sum_{n=2}^{N}\left(\log P_{t+1}^{(n-1)}-\log P_t^n\right)z_t^n \\
&= -\log P_t^{(1)}z_t^1+\sum_{n=2}^{N}\left(\bar{a}_{n-1}+\bar{\mathbf{b}}_{n-1}^{'}\left(\boldsymbol{\mu}+\boldsymbol{\rho}X_t\right)-\bar{a}_n+\bar{\mathbf{b}}_nX_t\right)z_t^n+\left(\sum_{n=2}^{N}\bar{\mathbf{b}}_{n-1}^{'}z_t^n\right)\varepsilon_{t+1} \\
&= B_t+\left(\sum_{n=2}^{N}\bar{\mathbf{b}}_{n-1}^{'}z_t^n\right)\varepsilon_{t+1} \\
&= B_t+\mathbf{d}_t^{'}\varepsilon_{t+1}
\end{aligned}$$

where $\mathbf{d}_t \equiv \sum_{n=2}^{N}\bar{\mathbf{b}}_{n-1}^{'}z_t^n$. Thus, the variance of arbitrager's portfolio return is approximated by $Var(R_{t+1}) \approx \mathbf{d}_t^{'}\Omega\mathbf{d}_t$. The right-hand side is

$$
\begin{aligned}
\frac{1}{2}\frac{\partial \text{Var}(R_{t+1})}{\partial z_t^n} &\approx \bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\left(\bar{\mathbf{b}}_1 s_t^2 + \cdots + \bar{\mathbf{b}}_{N-1} s_t^N\right) \\
&= \bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\left(\bar{\mathbf{b}}_1 z_t^2 + \cdots + \bar{\mathbf{b}}_{N-1} z_t^N\right) \qquad \text{(By market clearing conditions)} \\
&= \bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\begin{bmatrix} \bar{\mathbf{b}}_1 & \bar{\mathbf{b}}_2 & \cdots & \bar{\mathbf{b}}_{N-1} \end{bmatrix}\begin{bmatrix} s_t^2 \\ s_t^3 \\ \vdots \\ s_t^N \end{bmatrix} \\
&= \bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\begin{bmatrix} \bar{\mathbf{b}}_1 & \bar{\mathbf{b}}_2 & \cdots & \bar{\mathbf{b}}_{N-1} \end{bmatrix}\left(\boldsymbol{\kappa}_N + \tilde{\boldsymbol{\Psi}}_N X_t\right)
\end{aligned}
$$

Using the above expressions, the FOCs for n-period bonds can be approximated as:

$$
\begin{aligned}
&\left(\bar{a}_{n-1} + \bar{\mathbf{b}}_{n-1}'\mu - \bar{a}_n + \frac{1}{2}\bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\bar{\mathbf{b}}_{n-1} + \bar{a}_1\right) + \left(\bar{\mathbf{b}}_{n-1}'\boldsymbol{\rho} - \bar{\mathbf{b}}_n' + \bar{\mathbf{b}}_1'\right) X_t \\
&\qquad = \gamma\bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\begin{bmatrix} \bar{\mathbf{b}}_1 & \bar{\mathbf{b}}_2 & \cdots & \bar{\mathbf{b}}_{N-1} \end{bmatrix}\left(\boldsymbol{\kappa}_N + \tilde{\boldsymbol{\Psi}}_N X_t\right)
\end{aligned}
$$

Accordingly, we can derive the factor loading equations by comparing the coefficients.

$$
\begin{aligned}
\bar{\mathbf{b}}_n' &= \bar{\mathbf{b}}_{n-1}'\boldsymbol{\rho} - \gamma\bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\begin{bmatrix} \bar{\mathbf{b}}_1 & \bar{\mathbf{b}}_2 & \cdots & \bar{\mathbf{b}}_{N-1} \end{bmatrix}\tilde{\boldsymbol{\Psi}}_N + \bar{\mathbf{b}}_1' \\
\bar{a}_n &= \bar{a}_{n-1} + \bar{\mathbf{b}}_{n-1}'\boldsymbol{\mu} + \frac{1}{2}\bar{\mathbf{b}}_{n-1}'\boldsymbol{\Omega}\bar{\mathbf{b}}_{n-1} - \gamma\bar{\mathbf{b}}_{n-1}'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'\begin{bmatrix} \bar{\mathbf{b}}_1 & \bar{\mathbf{b}}_2 & \cdots & \bar{\mathbf{b}}_{N-1} \end{bmatrix}\boldsymbol{\kappa} + \bar{a}_1
\end{aligned}
$$