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Supply Constraints and Inflation Dynamics[*]

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Abstract

This paper analyzes the impact of supply constraints on inflation dynamics and its mechanisms from both empirical and theoretical perspectives. It also examines recent changes in the relationship between supply constraints and inflation dynamics, as well as measures to mitigate the effects of supply constraints on inflation. The analysis shows that the recent intensification of supply constraints affected Japan's inflation dynamics through the following channels. First, the intensification of labor and material supply constraints had a persistent impact on the inflation rate through mechanisms such as factor price increases. Second, the intensification of labor supply constraints contributed to the recent increase in inflation through nonlinear effects which amplify the demand elasticity of prices. The results also suggest that persistent supply constraints, under accommodative financial conditions, led to a recent rise in inflation expectations.

Furthermore, the analysis implies that inflationary pressures arising from intensifying supply constraints have become more frequent and significant in recent years. The further intensification of labor supply constraints could have a nonlinearly strengthening effect on inflationary pressures in the future. Promoting technological progress through firm-based initiatives and government policies—such as the adoption of AI—and facilitating labor mobility across industries and firms, will be important for easing supply constraints in Japan.

JEL Classification: E23, E24, E31, E37
Keywords: Supply Constraints, Inflation, Nonlinearity, Technological Progress

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1. Introduction

In the early 2020s, global inflation was triggered by rising commodity and food prices. Supply constraints in various fields are understood to have significantly contributed to the increase in inflation rates[1]. Furthermore, some argue that under these constraints, the inflationary effects of fiscal and monetary stimulus were amplified nonlinearly. Based on this experience, central banks and international organizations are highly cautious about the possibility that supply-driven inflationary pressures may become frequent and recurring, in different forms, in the future[2]. This indicates the need for further analysis on the changes in the environment surrounding economic activity and prices, as well as price formation mechanisms.

In Japan, the additional labor supply pool has been shrinking amid an aging population and declining birthrate. The economy is also vulnerable to global economic fragmentation due to its long and complex supply chains and high dependence on imported energy. Given these structural conditions, Japan may face supply constraints across the various market for factors of production, including labor and materials in the future. In this context, it is increasingly important to deepen analysis of the impact of supply constraints on inflation dynamics and its mechanisms in order to have a clear and precise understanding of the background to price developments and to compile an accurate outlook for inflation.

With this in mind, this paper analyzes the impact of supply constraints on inflation dynamics in Japan from both empirical and theoretical perspectives. Our analysis contributes to the following three strands of research.

First, this analysis relates to studies showing the impact of intensifying supply constraints on recent inflation rates and expectations. We use a structural Vector Autoregressive (SVAR) model with Japanese data, similar to prior studies by Ascari et al. (2024) and Diaz et al. (2024), which primarily focus on the United States and Europe[3]. In particular, this paper concentrates on the differences in the types of constrained production factors and the persistence of supply constraints.

Second, this paper relates to research on the nonlinearity of inflation dynamics. Our Dynamic Stochastic General Equilibrium (DSGE) model, which incorporates labor supply constraints, can be positioned within the prior studies, such as Boehm and Pandalai-Nayar

[1] The state of facing supply constraints is often defined as "the inability of supply to meet demand at prevailing prices" (Caldara et al., 2025). In this paper, terms such as supply constraint, supply bottleneck, supply disruption, and supply shortage, which are commonly used in prior studies, are considered synonymous.

[2] See, Powell (2025), Lagarde (2025), and Carstens (2022).

[3] Note that Fukunaga et al. (2025) and Kaihatsu et al. (2024) also use structural VAR models to analyze Japan's inflation rate.

(2022) and Comin et al. (2023), which focus on the United States and Europe. Our findings, which demonstrate that labor supply constraints can steepen the Phillips curve, have implications for discussions on the nonlinearity of the inflation rate in Japan (Sasaki et al., 2024; Yagi et al., 2025).

Third, this paper also contributes to the literature through a comprehensive review of Japan's past experiences with supply constraints, and analysis of the policy responses to these constraints.

This paper defines "supply constraints" as restrictions on the use of production factors. Therefore, intensified supply constraints lead to factor price increases through the steepening of the supply curve. Additionally, as the economic environment shifts, the intensification of supply constraints could become protracted, potentially making its effects more persistent. This mechanism is distinct from "supply shocks," which cause a shift in the supply curve. This paper also examines those environmental changes behind the supply constraints.

The rest of the paper is structured as follows. Section 2 reviews the facts concerning supply constraints. After surveying prior studies on the impact of recent supply constraints on inflation, the section discusses the environmental changes causing such constraints. Section 3 then analyzes the impact of recent supply constraints on inflation in Japan using a SVAR model. Section 4 constructs a DSGE model with labor supply constraints to reveal the effects of intensifying supply constraints on inflation dynamics. Section 5 examines policy responses to supply constraints by reviewing recent discussions and past policy measures addressing supply constraints in Japan, as well as conducting an analysis based on the DSGE model from the previous section. Section 6 concludes the paper.

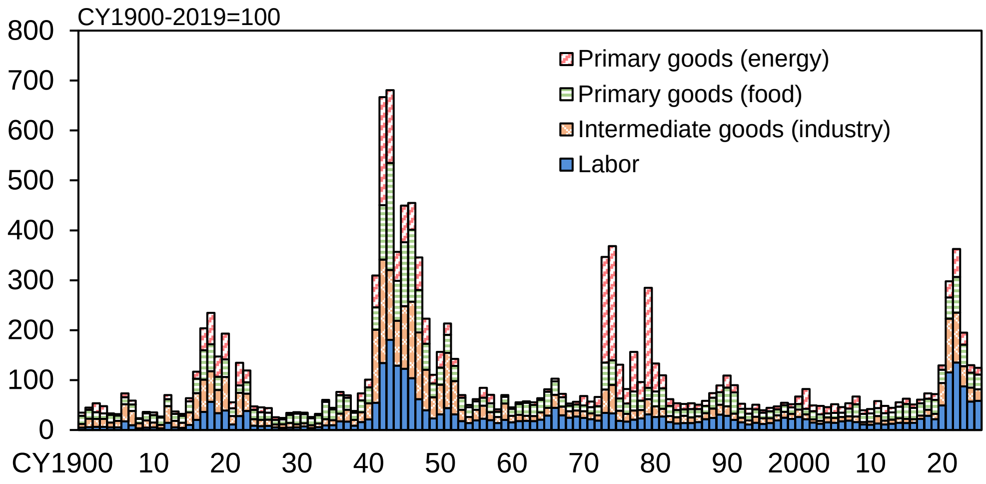
2. Review of Supply Constraints

2.1. Literature Review on the Impact of Supply Constraints on Inflation

Throughout the 2010s, as medium- to long-term inflation expectations were anchored and inflation rates remained steady in many countries, attention regarding inflation dynamics was primarily focused on demand-side factors. However, in recent years, the experience of global inflation following the pandemic has highlighted the importance of supply-side factors, particularly supply constraints in various fields, in shaping inflation dynamics. Research attention on this topic from both empirical and theoretical perspectives has been rapidly increasing.

Empirical evidence suggests that supply constraints across various production factors have contributed to the recent increase in inflation rates. Caldara et al. (2025) constructed the shortage index, which is defined as the fraction of news articles in major U.S. newspapers containing words indicating shortages in energy, food, industry, and labor. The shortage index shows that, during the recent period of global inflation, supply constraints intensified across a wide range of production factors, including primary goods such as energy and food, as well as intermediate goods and labor (Figure 1). This is very different from what we saw during events like the oil shocks of the 1970s.

(Figure 1) Shortage Index



Note: The shortage index is the fraction of news articles in major U.S. newspapers containing words indicating shortages, such as "shortage" or "bottleneck," related to energy, food, industry, or labor, out of the total number of articles.
Source: Caldara et al. (2025).

Specifically, supply constraints on intermediate goods arising in various forms within global supply chains are highlighted in many studies (Ascari et al., 2024; Bańbura et al., 2023; Carriere-Swallow et al., 2023; Diaz et al., 2024; Clark and Gordon, 2023; Tillmann, 2024, etc.)[4]. For instance, Ascari et al. (2024) employ a SVAR model that incorporates the Global Supply Chain Pressure Index (GSCPI), which is developed by Benigno et al. (2022). They demonstrate that supply chain disruptions contributed to the recent sharp increase in inflation rates. Furthermore, Diaz et al. (2024) discuss that in advanced economies, including Japan, the impact of global supply chain disruptions on inflation rates has intensified since the pandemic, with prolonged effects also observed in the United Kingdom and Germany. Tillmann (2024) argues that the impact of intensifying supply constraints on inflation rates is greater than the impact observed when constraints are eased, suggesting that the impact is asymmetric.

[4] The supply constraints on intermediate goods are attributable to several factors. First, there are shortages of semiconductors and other components due to factory closures during the pandemic (Celasun et al., 2022). Second, there are logistics issues, such as container shortages, port congestion, and delivery delays due to rerouting following the Red Sea blockade (Carriere-Swallow et al., 2023; Rusticelli and MacLeod, 2025).

Regarding production factors other than intermediate goods, labor supply constraints—reflecting factors such as shifts in worker preferences—have been identified as contributors to the acceleration of inflation rates in recent years in the United States and other countries (Bai et al., 2024; Benigno and Eggertsson, 2024). In addition, supply disruptions of Russian natural gas due to Russia's invasion of Ukraine (De Santis and Tornese, 2025; Eickmeier and Hofmann, 2025) and supply constraints on agricultural products due to extreme weather events such as droughts and floods (Kotz et al., 2025) have also been cited as factors that intensified inflationary pressures, mainly in Europe.

There has been much theoretical discussion of the various mechanisms which lead to supply constraints amplifying price fluctuations through nonlinearity. Mechanisms include: (1) the supply curve for goods and services becoming vertical for firms facing material or production capacity constraints (Balleer and Noeller, 2024; Boehm and Pandalai-Nayar, 2022, etc.), (2) the household labor supply curve becoming vertical due to labor supply constraints (Comin et al., 2023), and (3) a decline in wage rigidity due to tight labor market conditions (Benigno and Eggertsson, 2023).

2.2. Environmental Changes Behind Supply Constraints

Previously, "rare and temporary" factors, such as factory closures and labor disputes, were identified as the primary causes of these supply constraints. However, there is a growing view that the presence of "frequent and persistent" factors is increasing[5]. These include: (1) climate change, (2) the fragmentation of the global economy and heightened geopolitical tensions, and (3) an aging population and declining birthrate.

Climate change could constrain supply through so-called "physical risks" and "transition risks." From the perspective of physical risks, the increase in natural disasters leads to reduced production of primary goods, such as agricultural products, and disrupts logistics networks (Kotz et al., 2024; De Winne and Peersman, 2021). Additionally, there is a reduction in the labor supply due to increased health risks, such as heatstroke (Dasgupta et al., 2021). From the perspective of transition risk, the transition to a decarbonized society may lead to unstable fossil fuel supplies due to reduced investment in development (IEA, 2021).

Regarding the fragmentation of the global economy and heightened geopolitical tensions, economic blocs may lead to instability in the procurement of goods with concentrated supply sources, such as mineral resources, and may necessitate the

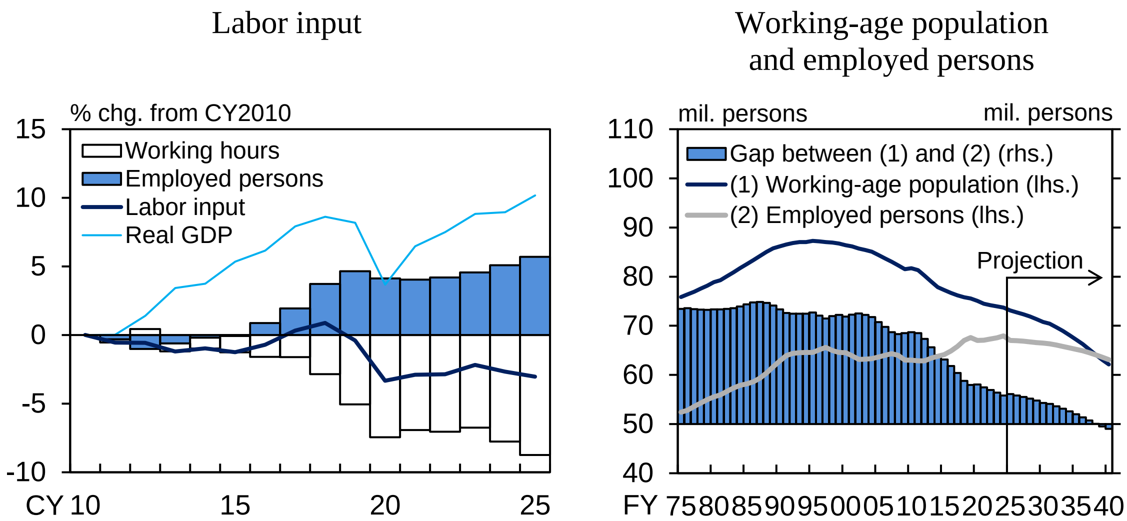
[5] For example, Baldwin et al. (2023) argue that the nature of recent supply chain shocks has shifted from traditional shocks—confined to individual firms or specific products—to shocks that ripple across multiple markets and goods, impacting broad sectors and regions. They also cite climate change, geopolitical tensions, and digital disruption as sources of such shocks.

restructuring of supply chains (Alvarez et al., 2023; Gopinath et al., 2025). Some also argue that diverting shipments due to intensified geopolitical conflicts could result in stronger logistical constraints, leading to longer delivery times and reduced transport volumes (UNCTAD, 2024).

Regarding an aging population and declining birthrate, Goodhart and Pradhan (2020) argue that, in the long run, the declining labor supply from emerging economies like China will act as a global negative supply shock through supply chains.

In this regard, Japan has offset the downward pressure on the labor supply caused by demographic trends by increasing the labor participation of women and seniors. However, the "M-shaped curve" in the female labor force participation rate is gradually flattening, and the baby boomer generation has entered the late elderly stage. Against this backdrop, the potential for additional labor supply is diminishing (Figure 2). To further tap into the potential labor supply, several measures have been proposed, such as boosting working hours by increasing women's regular employment rates (thereby eliminating the so-called "L-shaped curve"), promoting the utilization of secondary jobs, and increasing the number of foreign workers. However, it should be noted that these measures require policy initiatives and societal discussion (e.g., Cabinet Office, 2022).

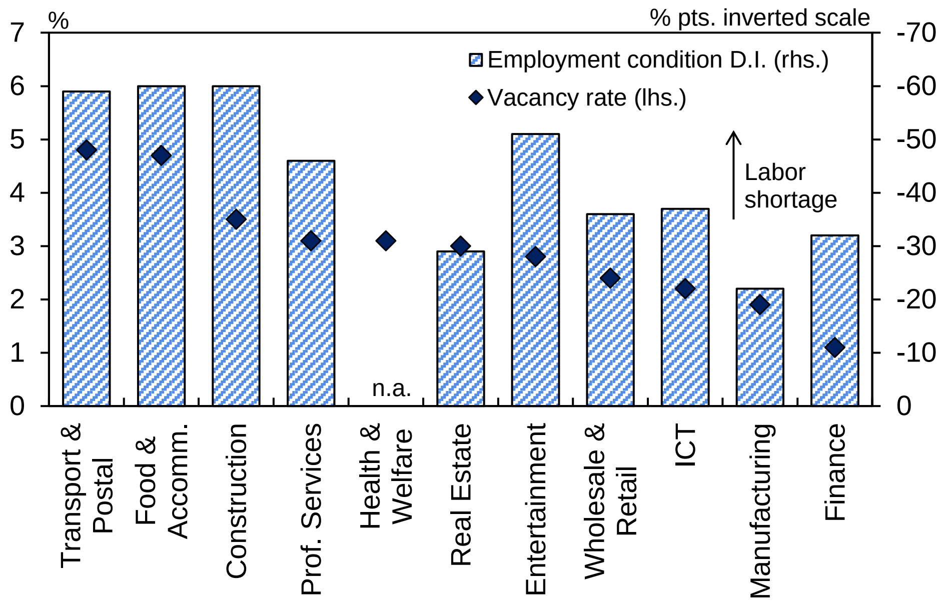
(Figure 2) Aggregate Labor Supply



Note: Figures for 2025 in the left panel are January-June averages. In the right panel, the projection for the working-age population is from the National Institute of Population and Social Security Research. The projection for the number of employed persons is calculated based on projections from the Japan Institute for Labour Policy and Training.
Sources: Ministry of Health, Labour, and Welfare; Ministry of Internal Affairs and Communications; Cabinet Office; National Institute of Population and Social Security Research; Japan Institute for Labour Policy and Training.

Furthermore, vacancy rates by industry reveal that labor shortages are not occurring uniformly across the economy (Figure 3). The reduction in the pool of aggregate labor supply is likely to exacerbate these labor shortages in certain industries.

(Figure 3) Labor Shortage by Industry (as of 2025/Q2)



Sources: Ministry of Health, Labour, and Welfare; Bank of Japan.

3. The Impact of Recent Supply Constraints on Inflation

This section analyzes the impact of recent supply-side shocks on Japan's inflation rate through supply constraints, using a SVAR model that accounts for differences in the types of constrained production factors and the persistence of supply constraints.

3.1. Overview of the SVAR Model

Outline of the model

First, we consider the following VAR model with six variables: real output, CPI excluding fresh food and energy, labor input (number of employed persons multiplied by working hours), real intermediate inputs, the shortage index for Japan, and nominal hourly wages[6]. The shortage index for Japan, as calculated by Caldara et al. (2025), is derived in the same way as the shortage index shown in Figure 1, but restricted to articles that reference Japan or its major cities.

[6] In the SVAR model of this paper, we consider "materials," such as energy and intermediate goods, to be production factors, alongside "labor." Therefore, we use real output, defined as real GDP (real value added) plus real intermediate inputs, as the corresponding production quantity. In addition, CPI figures exclude the reduction in mobile phone charges and the effects of the consumption tax hikes. For details on the data, see Appendix 1.

$$y_t = \sum_{\ell=1}^{p} A_\ell y_{t-l} + A_0 + u_t,$$

where y_t represents an $n \times 1$ vector of endogenous variables ($n = 6$), and $u_t \sim \mathrm{N}(0, \Sigma)$ is an $n \times 1$ vector of error terms. In addition, A_ℓ is an $n \times n$ coefficient matrix and A_0 is an $n \times 1$ vector of constants. The lag order (p) is set to 2 based on the AIC.

Assuming a relationship between the error terms (u_t) and the structural shocks ($\varepsilon_t \sim \mathrm{N}(0, \mathrm{I_n})$) in the form $\varepsilon_t = Bu_t$ allows us to identify the structural shocks and obtain the following SVAR model.

$$By_t = \sum_{\ell=1}^{p} B_\ell y_{t-l} + c + \varepsilon_t,$$

where $B_\ell = BA_\ell$ is an $n \times n$ coefficient matrix and $c = BA_0$ is an $n \times 1$ vector of constants.

Identification of Structural Shocks

This paper considers demand shocks and three types of supply constraint shocks to be structural shocks (ε_t). To identify these shocks, we use short-run sign restrictions and a long-run zero restriction. These restrictions are presented in Table 1. We identify four structural shocks for the six endogenous variables, allowing for the existence of shocks that do not satisfy any of the identification restrictions, as in Forbes et al. (2020).

(Table 1) Identification Restrictions (Short-run/Long-run)

	Shocks			
	Demand	Persistent supply constraints		Temporary supply constraints
		Labor	Material	
Real output	+	−	−	−/0
CPI	+	+	+	+
Labor input		−		− and/or
Real intermediate inputs			−	−
Shortage index (Japan)		+	+	+
Nominal wages	+	+		

Note: "+" indicates a short-run restriction where the contemporaneous response is positive, "−" indicates a short-run restriction where the contemporaneous response is negative, and "0" indicates a long-run restriction where the cumulative impulse response is zero.

First, we need to distinguish the supply constraint shocks discussed in this paper from standard supply shocks or cost-push shocks. Similar to the identification of supply chain disruption shocks by Ascari et al. (2024) and Clark and Gordon (2023), we distinguish supply constraint shocks from other shocks based on whether a reduction in the supply of production factors is accompanied by intensified supply constraints. Specifically, in identifying supply constraint shocks, we impose an additional restriction—the shock must increase the shortage index—in addition to reducing labor input (or real intermediate inputs) and real output, while raising the CPI. Thus, the supply constraint shocks in this paper capture the changes in the degree of supply constraints, either their intensification or relaxation, within an economy that inherently experiences a certain degree of these constraints due to various frictions.

This paper also classifies supply constraint shocks as either persistent or transitory. Referencing Furlanetto et al. (2025) and Fukunaga et al. (2025), we isolate transitory shocks from persistent shocks by imposing a long-run zero restriction, ensuring that these shocks have no impact on real output in the long term.

Furthermore, this paper classifies persistent supply constraint shocks into two categories based on the constrained production factor: labor and material. A labor supply constraint shock captures a tightening of labor supply constraints arising from household labor supply stances (e.g., labor force participation or working hours) or labor market frictions (e.g., mismatches). It is identified by imposing an additional short-run sign restriction that the shock reduces labor input while increasing nominal wages. On the other hand, material supply constraint shocks capture shocks stemming from intensifying supply constraints on production factors other than labor input, such as intermediate goods and energy. This shock encompasses supply chain disruption shocks and energy supply shocks in prior studies. Following these studies, we identify a material supply shock by imposing an additional short-run sign restriction that the shock reduces real intermediate inputs. Since material supply constraints are expected to increase the inflation rate while decreasing real wages due to reduced labor demand, we do not impose a restriction on nominal wages.

Finally, demand shocks are identified using the standard short-run sign restriction where demand shocks move real output, CPI, and nominal wages in the same direction. Consequently, shocks that do not satisfy any of these restrictions would include, for example, cost-push shocks.

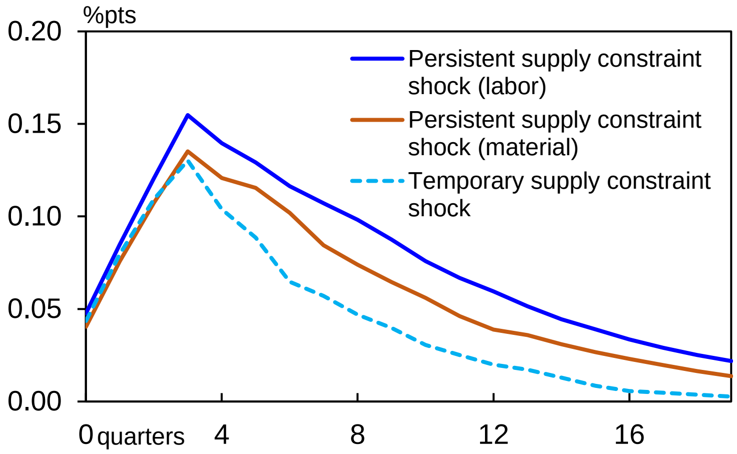
We conduct Bayesian estimation, following procedures similar to those of Forbes et al. (2020) and Fukunaga et al. (2025). Our estimation covers the period from 1994/Q2 to 2025/Q1, for which data is available[7].

[7] The hyperparameters of the Minnesota prior are set to the standard values: $\lambda_1 = 0.1$, $\lambda_2 = 0.5$, $\lambda_3 = 1$, $\lambda_4 = 100$. We use an algorithm based on Binning (2013). 10,000 iterations after 100,000 iterations of burn-in period are used for the estimation.

3.2. Impact of Recent Supply Constraints

We examine the characteristics of the impact of supply constraint shocks on the inflation rate. Figure 4 shows the impulse responses of the inflation rate to the three types of supply constraint shocks[8].

(Figure 4) Impulse Response of the CPI Inflation Rate (excluding fresh food and energy)



Note: The median impulse responses of the year-on-year rate of change in the CPI (excluding fresh food and energy) to one standard deviation supply constraint shocks. Figures are calculated by aggregating the responses of the quarter-on-quarter changes over four quarters.

Although the restrictions on the inflation rate are the same in identifying these supply constraint shocks, there are notable differences among the impulse responses. For temporary supply constraint shocks, the inflation rate accelerates over the next year and then declines significantly. On the other hand, for persistent supply shocks of labor or materials, the response of the inflation rate is larger, and the pace of decline is slower. These responses also reveal that labor supply constraints have a more persistent impact on the inflation rate than material supply constraints do.

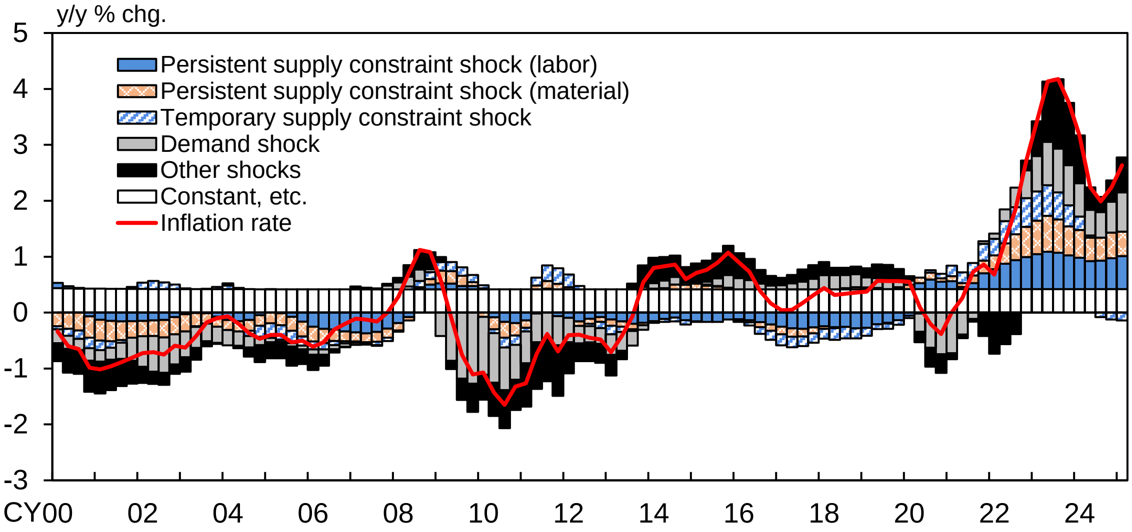
Figure 5 presents the historical decomposition of Japan's inflation rate based on the identified shocks and estimated impulse response functions.

Based on this decomposition looking back at inflation trends since the pandemic, the negative demand shock triggered by the pandemic significantly depressed inflation rates from 2020 through to the first half of 2021. During the period of sharply rising inflation rates up to mid-2023, three factors drove inflation upwards: (1) positive demand shocks, primarily driven by pent-up demand following the pandemic; (2) cost-push shocks including the yen's depreciation (labeled "Other shocks" in the figure); and (3) an expansion of upward pressure from various supply constraint shocks. Through early 2025, the end of estimation period, the upward pressure from persistent supply constraint shocks

[8] Details of the identified structural shocks and impulse responses are presented in Appendix 1.

related to labor and materials remained elevated. The impact of "Other shocks" diminished through mid-2024 as the effect of the yen's depreciation faded. However, it has since expanded again amid rising rice prices.

(Figure 5) Historical Decomposition of the CPI Inflation Rate (excluding fresh food and energy)

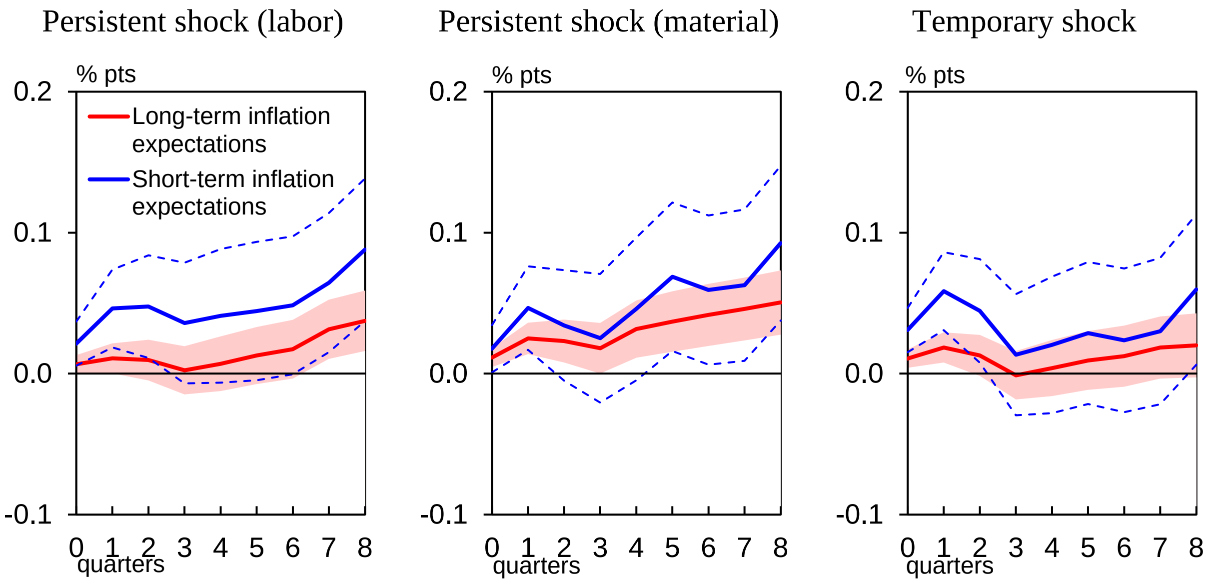


Note: Historical decomposition of the year-on-year rate of change in the CPI (excluding fresh food and energy). Figures are calculated by aggregating the historical decomposition of the quarter-on-quarter changes over four quarters.

Next, we will focus on the recent expansion of the impact of supply constraint shocks, and more specifically, its context. When it comes to persistent labor supply constraints, the potential for additional labor supply has decreased due to the following factors: a declining trend in working hours resulting from the "Work Style Reform" and strengthened working hour regulations, the resolution of the "M-shaped curve" in the female labor force participation rate, and the baby boomer generation entering the late elderly stage. The expansion of persistent supply constraint shocks on materials likely stems from surging commodity and food prices due to extreme weather events coupled with repeated supply chain disruptions. This expansion may also reflect the instability in material procurement caused by the fragmentation of the global economy following Russia's invasion of Ukraine and the emergence of geopolitical risks, such as the Red Sea crisis. The impact of temporary supply constraints appears to include factors beyond those mentioned earlier, such as the semiconductor shortage through 2023.

Our SVAR model does not include inflation expectations as an endogenous variable to avoid excessive model complexity due to an increased number of shocks and identification restrictions, and to focus on the effects of various supply constraint shocks on the inflation rate. However, it is also important to consider the possibility that supply constraint shocks affect both the inflation rate and inflation expectations simultaneously. Therefore, we estimated the impulse responses of short-term (1-year) and long-term (10-year) inflation expectations to supply constraint shocks based on local projection with supply constraint shocks identified by the SVAR model[9,10].

(Figure 6) Impulse Responses of Inflation Expectations to Supply Constraint Shocks



Note: Impulse responses of short-term (1-year) and long-term (10-year) inflation expectations to one standard deviation supply constraint shocks. The bands indicate the 16th to 84th percentile range.

Figure 6 presents the estimation results, indicating that persistent supply constraint shocks related to labor and materials pushed up long-term inflation expectations with a lag. The result is partly attributed to the expectation that accommodative financial conditions would be maintained while long-term inflation expectations remained below 2%. Conversely, temporary supply constraint shock appears to have had no statistically significant impact on long-term inflation expectations in the long run.

3.3. Recent Changes

Here, we examine the reasons behind the significant impact of supply constraints on Japan's inflation rate in recent years from two perspectives: (1) the nature of the shocks, and (2) how the inflation rate responds to these shocks.

One way to analyze changes in the nature of supply constraint shocks is to divide the sample into pre- and post-pandemic periods and compare the identified shocks in terms of their direction and magnitude[11]. Figure 7 shows the results of this comparison for persistent

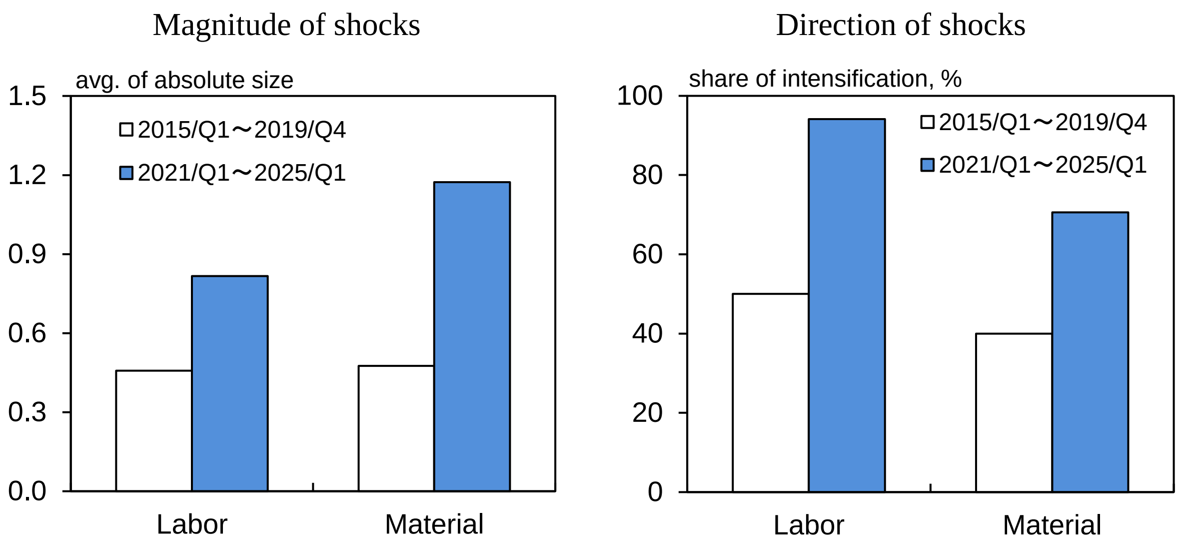
[9] This two-stage approach has been adopted by Adolfsen et al. (2024) and others.

[10] In the estimation, we include the following control variables with lags of one to two periods: (1) inflation expectations (estimates from Osada and Nakazawa, 2024), (2) output gap, (3) nominal effective exchange rate, (4) crude oil price, (5) shadow rate (estimates from Krippner, 2013).

[11] De Santis and Tornese (2025) also discuss changes in the nature of shocks after the pandemic by examining the magnitude of shocks.

supply constraint shocks. The figure suggests that, after the pandemic, the frequency of shocks in the direction of tighter constraints increased and the magnitude of these shocks expanded. Focusing on differences by type of production factor, labor supply constraints continuously intensified due to demographic factors. Meanwhile, the impact of material shocks expanded more significantly reflecting repeated large-scale disruptions in the supply chain.

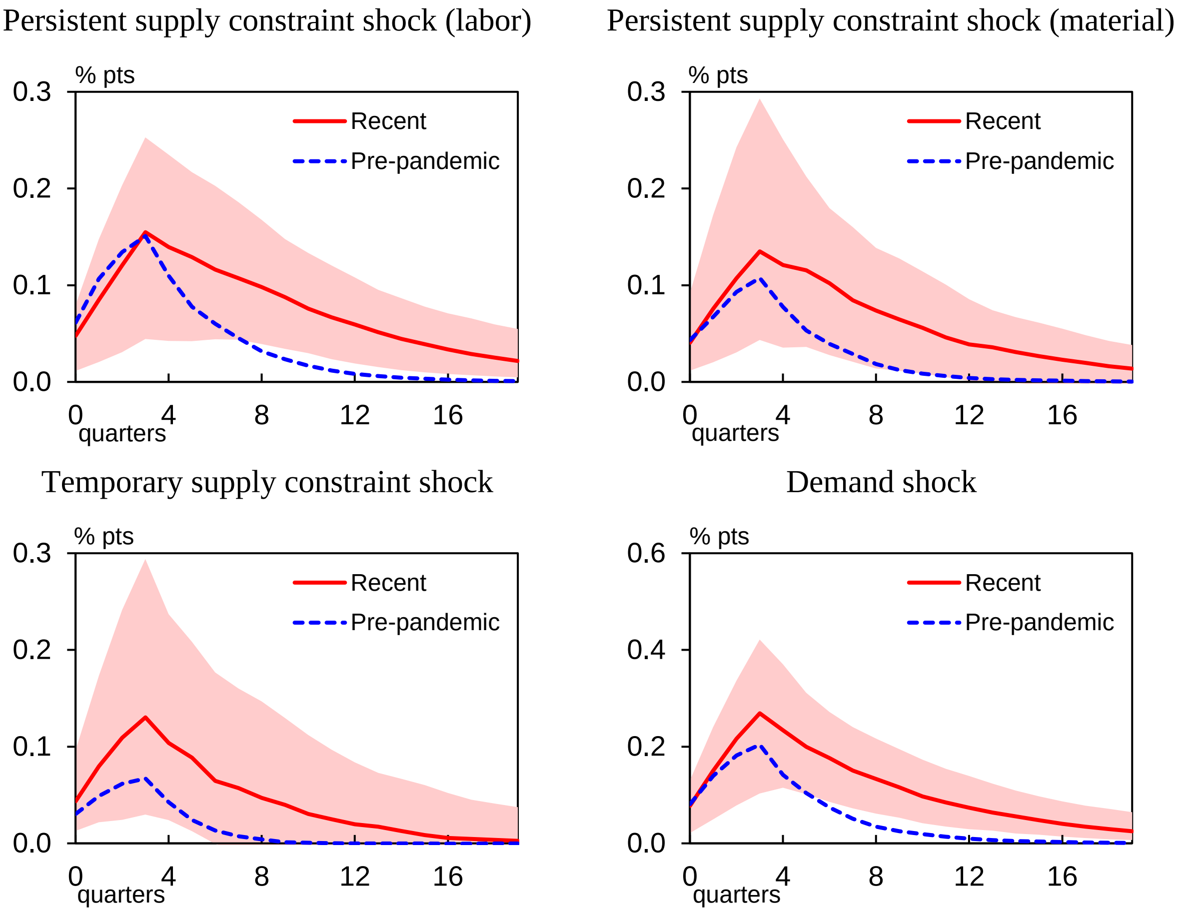
(Figure 7) Changes in the Nature of Persistent Supply Constraint Shocks



Note: Figures are calculated from the average of identified structural shocks. The left panel shows the average absolute value of persistent supply constraint shock related to labor (materials) for each period. The right panel shows the proportion of quarters when the persistent supply constraint shock related to labor (materials) was positive (the shock was pushing up the shortage index).

Regarding changes in the inflation rate's response to shocks, we compare the baseline impulse response with that of the estimate based on the period ending in 2019/Q4 subsample, prior to the pandemic's onset. As shown in the upper left panel of Figure 8, the median impulse response of the inflation rate to a persistent labor supply constraint shock exceeds pre-pandemic levels starting in the second year. This suggests that the impact of persistent labor supply constraints has grown in recent years. Additionally, the median impulse response to a demand shock in the lower right panel of Figure 8 exceeds pre-pandemic levels approximately one year after the shock. This suggests that the upward pressure on inflation from increased aggregate demand may have strengthened in recent years. The next section therefore examines the mechanism by which price fluctuations in response to changes in aggregate demand amplify, with a focus on labor supply constraints.

(Figure 8) Changes in the Impulse Response of the CPI Inflation Rate (excluding fresh food and energy)



Note: Figures are the median impulse responses of the year-on-year rate of change in the CPI (excluding fresh food and energy) to a supply constraint shock or positive demand shock. The shock occurs in period 0. The shock magnitude is one standard deviation based on samples up to 2025/Q1. The solid lines show estimates based on the sample up to 2025/Q1; the dotted lines show estimates based on the sample up to 2019/Q4. The band indicates the 16th to 84th percentile range of the estimates based on the sample up to 2025/Q1.

4. Inflation Dynamics under Supply Constraints

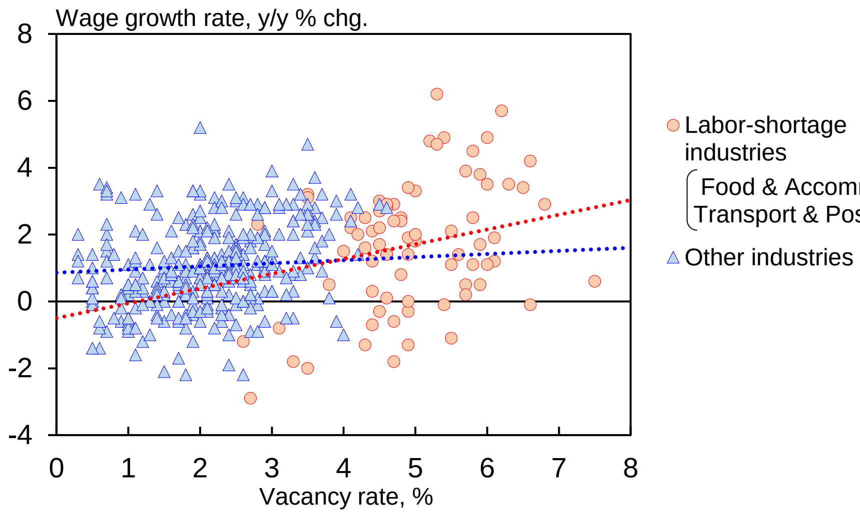
This section constructs and estimates a DSGE model incorporating the mechanism by which labor supply constraints amplify inflation fluctuations. It also quantitatively examines the impact of labor supply constraints on inflation dynamics in Japan.

4.1. Empirical Facts Behind the Model

As outlined in Section 2, Japan's potential for additional labor supply is shrinking, and labor shortages in certain industries may intensify in the future. As suggested by previous studies, in industries facing severe labor shortages, a further worsening of labor shortages could lead to more substantial wage increases. Additionally, firms constrained by labor shortages may raise prices more significantly in response to increased demand.

To gain insights into these possibilities, here we examine Japan's data. First, the scatter plot of vacancy rates and wage growth rates indicates that industries facing severe labor shortages, such as "Food and Accommodation" and "Transportation and Postal Services", exhibit a somewhat steeper relationship compared to other industries (Figure 9).

(Figure 9) Relationship between Vacancy Rates and Wage Growth Rates



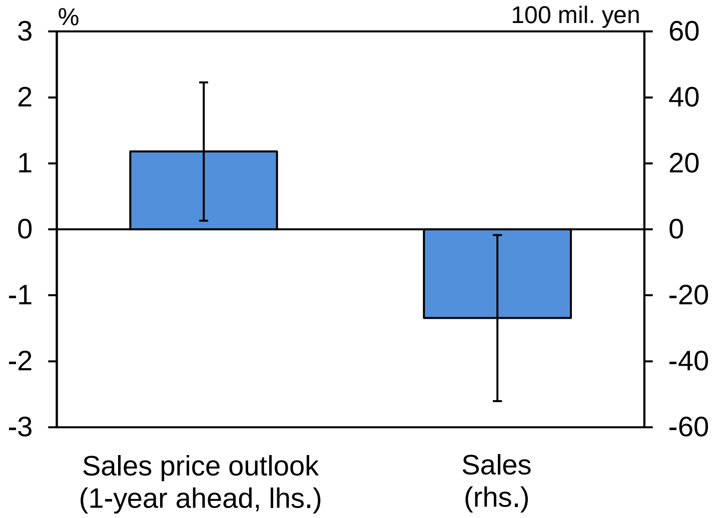
Note: Plot of vacancy rates and wage growth rates by industry from 2016/Q1 to 2025/Q2. Wage growth rate represents the year-on-year rate of change in nominal regular wages for general workers (based on "continuing observations").
Source: Ministry of Health, Labour and Welfare.

Next, to examine how firms facing labor shortages price their goods and services, we use firms' one-year sales price outlook from *Tankan* survey (Short-Term Economic Survey of Enterprises in Japan) micro data. We compare the outlook of firms whose production capacity appears to be constrained by labor shortages with that of firms that seem to operate their production and business activities without constraints (Figure 10). Specifically, we sample firms that reported "excess demand" for domestic goods and services, as well as "excess" production and business equipment. We then compare firms experiencing "shortages" in employees with firms not experiencing such shortages[12].

First, holding other conditions constant, we compare the sales of these two groups. Firms reporting "shortages" in employees have lower sales, suggesting that labor shortages may constrain the supply of these firms. Then, a comparison of sales price outlooks reveals that firms reporting "shortages" in employees have a sales price outlook that is 1.2 percentage points higher than firms without such a shortage. This suggests that firms constrained by labor shortages may raise prices more aggressively, as they find it difficult to increase supply even when demand is strong.

[12] The average sales price outlook for this sample is +2.0% in the year-on-year change.

(Figure 10) Impact of Supply Constraints due to Labor Shortages on Firms' Sales Price Outlook and Sales



Notes: 1. The left bar chart shows the estimated coefficient (bands indicate the 90% confidence interval) from a fixed-effects model with the *Tankan*'s sales price outlook (1 year ahead) as the dependent variable and a labor shortage dummy variable (1 if assessment on employment condition is "shortage," 0 if "excess" or "adequate") as the independent variable. The right bar chart shows the estimates when sales is used as the dependent variable. Control variables include assessment on business condition and input prices, and time dummies. Sales price outlook (1-year ahead) is coded as follows: "+20% or more" = +20%, "around +15%" = +15%, ..., "-20% or less" = -20%.

2. The sample consists of firms that reported "excess demand" for domestic manufactured goods and services, and "excess" for assessment on production and business equipment. The estimation period is March 2014 to June 2025. The number of observations is 1,306 (523 unique firms).

3. Standard errors are calculated using cluster standard errors.

Source: Bank of Japan.

4.2. Overview of the DSGE model

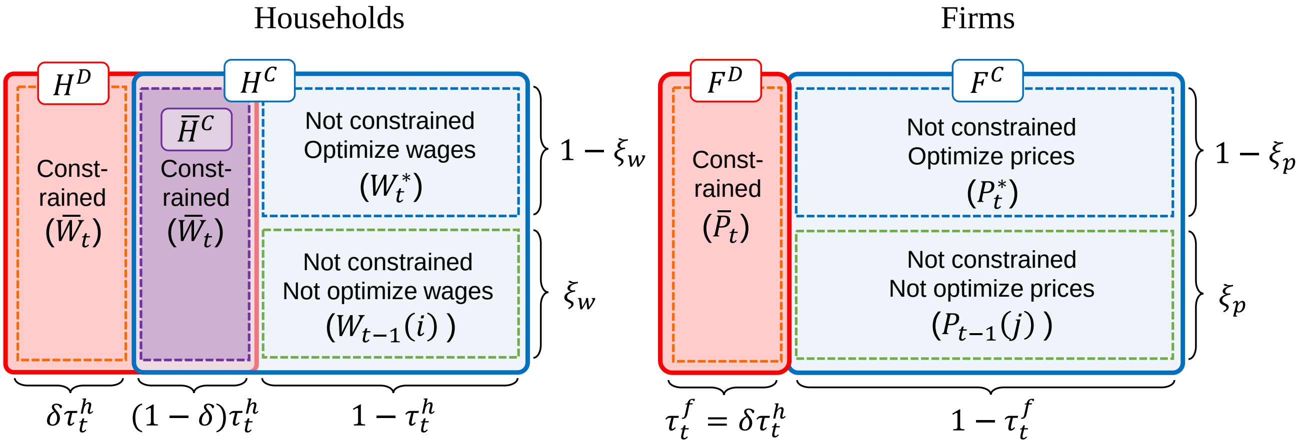
Features of the Model

Based on the above observations, the model presented in this section assumes that severe labor shortages could arise in certain jobs within the economy. The model also considers that in jobs with severe labor shortages, the demand elasticity of wages is higher due to limited labor supply. Furthermore, the model considers that some firms producing goods using such labor face supply constraints due to labor shortages, which makes their sales prices more sensitive to demand fluctuations.

Specifically, we simplify and incorporate these features into the New Keynesian model of Erceg et al. (2000), in which households supply differentiated labor. Labor supply constraints arising in certain jobs are expressed by making the labor supply curve of some households vertical. The feature that firms using these jobs for production may face supply constraints is represented by the assumption that some of the firms matched with constrained households are unable to access labor from other households. This causes the supply curve of these firms to become vertical, implying that they significantly raise sales prices in response to an increase in demand since they are unable to increase output levels.

Below, we describe the model setup concerning wage and price determination, the main focus of this section (see Appendix 2 for model details). The model includes multiple types of firms and households, differentiated by whether they face supply constraints or optimize their prices or wages. See Figure 11 for details.

(Figure 11) Classification of Households and Firms Based on the Presence of Supply Constraints and Differences in Wages and Prices



Note: For households (firms) unable to optimize wages (prices), wages (prices) are indexed to the previous period's inflation and the steady state inflation.

Labor Supply Constraint

Household $i \in [0,1]$ supplies differentiated labor $L_t(i)$. We assume that in period t, labor supply of $\tau_t^h \in [0,1]$ of households is constrained at the upper limit. That is, we assume labor supply of these households is fixed at $L_t(i) = \bar{L}$[13]. Conversely, labor supply of the remaining households, accounting for the proportion $1-\tau_t^h$, faces no constraints. These households are assumed to flexibly supply labor demanded at the wage level they set (the details of which are provided later in this section).

The proportion of households facing labor supply constraints, τ_t^h, is assumed to develop according to the following stochastic process.

$$\log\theta_t = (1-\rho_\tau)\log\theta + \rho_\tau \log\theta_{t-1} + \epsilon_t^\tau, \quad (1)$$

$$\theta_t = \left(1-\tau_t^h\right)^{-1}, \quad (2)$$

where $\theta = 1/(1-\tau^h)$ is the steady-state value of θ_t (τ^h is the steady state value of τ_t^h). In this model, an increase in τ_t^h is interpreted as the intensification of labor supply constraints.

[13] $\bar{L}$ is assumed to be sufficiently below the average level of labor input in the steady state.

Firms' Production Function

An intermediate goods producer (hereafter referred to as "firm" in this section) $j \in [0,1]$ produces differentiated goods using only labor. That is, the output of firm j, $Y_t(j)$, is given as follows.

$$Y_t(j) = A_t L_t(j), \tag{3}$$

where A_t and $L_t(j)$ represent the level of technology and labor input of firm j, respectively.

Household-Firm Matching and Two Labor Markets

At the beginning of each period, firms are assumed to be randomly matched with one of the households. Therefore, the proportion of firms paired with households under supply constraints is τ_t^h. We assume a proportion δ of them, i.e.,

$$\tau_t^f = \delta \tau_t^h \tag{4}$$

of pairs is assigned to a "decentralized market" (the sets of households and firms in this market are denoted as H^D and F^D, respectively). Firms in this market are assumed to have no access to labor supplied by households outside their pair. Therefore, the labor input of firm $j \in F^D$ becomes $L_t(j) = \bar{L}$, and these firms face production constraints due to labor shortages (i.e., $Y_t(j) = A_t \bar{L}$).

The remaining proportion of pairs $(1 - \tau_t^f)$ is assigned to the "centralized market" (the sets of households and firms in this market are denoted as H^C and F^C, respectively). Labor supplied by household $i \in H^C$ is aggregated as follows and used by firm $j \in F^C$.

$$L_t(j) = \left(\left(1 - \tau_t^f\right)^{-\lambda_t^w} \int_{H^C} L_t(i,j)^{1-\lambda_t^w} \, di \right)^{\frac{1}{1-\lambda_t^w}}, \tag{5}$$

where $L_t(i,j)$ represents the labor of household i used by firm j. The multiplier $\left(1 - \tau_t^f\right)^{\frac{\lambda_t^w}{\lambda_t^w - 1}}$ is for normalization[14], and λ_t^w is the inverse of the wage elasticity of labor demand in absolute term. Then, the demand function for labor by household $i \in H^C$ is as

[14] This term adjusts the love-of-variety effect of the CES function in a following way: The total labor input of firm j equals the sum of labor inputs from each household ($L_t(j) = \bar{L}$) when firm j obtains an equal amount of labor from all households ($L(i,j) = \left(1 - \tau_t^f\right)^{-1} \bar{L} \; \forall \, i \in H^C$).

follows.

$$L_t(i) = \left(\frac{W_t(i)}{W_t}\right)^{-\frac{1}{\lambda_t^w}} L_t, \tag{6}$$

where $W_t(i)$ is the nominal wage for labor supplied by household i. L_t is the average labor input in the centralized market, expressed as $L_t = \left(1 - \tau_t^f\right)^{-1} \int_{F^C} L_t(j)\ dj$, and W_t is the nominal wage index in the centralized market, expressed as $W_t = \left\{\left(1 - \tau_t^f\right)^{-1} \int_{H^C} W_t(i)^{(\lambda_t^w - 1)/\lambda_t^w}\ di\right\}^{\lambda_t^w/(\lambda_t^w - 1)}$.

Wage Setting in the Centralized Market

Among the households in the centralized market (household $i \in H^C$), the set of constrained households is denoted as $\bar{H}^C \subseteq H^C$. The nominal wage $\bar{W}_t$ for labor by household $i \in \bar{H}^C$ is assumed to be determined at the point where the labor demand curve in Equation (6) intersects the vertical labor supply curve ($L_t(i) = \bar{L}$)[15].

$$\bar{W}_t = \left(\frac{L_t}{\bar{L}}\right)^{\lambda_t^w} W_t. \tag{7}$$

On the other hand, for households not subject to labor supply constraints (i.e., $i \in (H^C \setminus \bar{H}^C)$), we assume Calvo-type wage-setting. Specifically, we assume that the nominal wages for $1 - \xi_w$ of households are optimized to W_t^*, while the wages for the remaining fraction, ξ_w, are indexed to the previous period's inflation and the steady state inflation.

Price Setting in the Centralized Market

As firms in the centralized market (firm $j \in F^C$) use aggregated labor as shown in Equation (5), their nominal marginal cost (MC_t) is as follows.

$$MC_t = \frac{W_t}{A_t}.$$

We assume Calvo-type pricing for firm $j \in F^C$. Specifically, we assume that the nominal prices for $1 - \xi_p$ of firms are optimized to P_t^*, while the nominal prices for the remaining fraction, ξ_p, are indexed to the previous period's inflation and the steady state

[15] The assumption that wages are determined on the labor supply curve implies that the household labor wedge (the gap between real wages and households' desired wages) does not arise under supply constraints. Therefore, in this model, an increase in households facing labor supply constraints is expected to reduce the overall labor wedge of households by lowering wage rigidity.

inflation.

Price Setting in the Decentralized Market

The price ($\bar{P}_t$) set by the firm in the decentralized market (firm $j \in F^D$) is determined at the point where the demand curve ($Y_t(j) = (P_t(j)/P_t)^{-\frac{1}{\lambda_t^p}} Y_t$; where Y_t is real GDP) intersects the vertical supply curve ($Y_t(j) = A_t \bar{L}$). That is,

$$\bar{P}_t = \left(\frac{Y_t}{A_t \bar{L}}\right)^{\lambda_t^p} P_t, \tag{8}$$

where λ_t^p is the inverse of the price elasticity of demand in absolute terms.

Wage Setting in the Decentralized Market

Nominal wages in decentralized markets should be determined through negotiations between paired households and firms, making it natural to assume Nash bargaining or a similar mechanism. However, as shown in Equation (8), the price set by firms in the decentralized market (firm $j \in F^D$), $\bar{P}_t$, is determined independently of wages. Therefore, the nominal wage of household $i \in H^D$ does not directly affect prices. Given this, we avoid unnecessary complications by introducing Nash bargaining. Instead, we simply assume that the nominal wage of household $i \in H^D$ is $\bar{W}_t$ which is the nominal wage for households facing labor supply constraints in the centralized market (i.e., household $i \in \bar{H}^C$).

Aggregation of Wages and Prices

The aggregation formula for the nominal wage W_t in the centralized market is as follows (omitting the indexation term).

$$\begin{aligned}(1-\delta\tau_t^h) W_t^{1-\frac{1}{\lambda_t^W}} &= (1-\delta)\tau_t^h \bar{W}_t^{1-\frac{1}{\lambda_t^W}} + (1-\tau_t^h)(1-\xi_w)(W_t^*)^{1-\frac{1}{\lambda_t^W}} \\ &\quad + (1-\tau_t^h)\xi_w \int_0^1 W_{t-1}(i)^{1-\frac{1}{\lambda_t^W}} \, di.\end{aligned} \tag{9}$$

As τ_t^h increases, the weight of the nominal wage $\bar{W}_t$ for constrained households, i.e., $(1-\delta)\tau_t^h$, rises. As suggested by Equation (7), $\bar{W}_t$ is more sensitive to fluctuations in aggregate demand than the aggregated nominal wage W_t.[16] Therefore, when τ_t^h is

[16] Taking the logarithm of both sides of Equation (7) and differentiating with respect to the demand shock $\log d_t$, we can confirm $\frac{\partial \log \bar{W}_t}{\partial \log d_t} = \frac{\partial \log W_t}{\partial \log d_t} + \lambda_t^w \frac{\partial \log L_t}{\partial \log d_t} > \frac{\partial \log W_t}{\partial \log d_t}$.

large—that is, when labor supply constraints are intense—the demand sensitivity of the aggregated nominal wage W_t is higher.

Furthermore, the aggregation formula for the nominal price P_t is as follows.

$$P_t^{1-\frac{1}{\lambda_t^p}} = \tau_t^f \bar{P}_t^{1-\frac{1}{\lambda_t^p}} + (1-\tau_t^f)(1-\xi_p)(P_t^*)^{1-\frac{1}{\lambda_t^p}} + (1-\tau_t^f)\xi_p P_{t-1}^{1-\frac{1}{\lambda_t^p}} \qquad (10)$$

From this, we see that when labor supply constraints intensify—that is, when τ_t^h is larger—demand sensitivity of price gets higher via two channels. First, as mentioned earlier, the number of households facing constraints increases, raising the demand sensitivity of nominal wages W_t (Channel 1). Since the price optimized in period t, P_t^*, is determined with reference to the nominal wage W_t, P_t^* becomes more sensitive to demand fluctuations, thereby increasing the demand sensitivity of P_t. The second channel is that the weight of the price set by firms facing labor shortages, $\bar{P}_t$, increases in the price index P_t (Channel 2). As suggested by Equation (8), $\bar{P}_t$ is more sensitive to demand fluctuations than the general price level P_t.[17] Therefore, an increase in the proportion of firms facing constraints, i.e., $\tau_t^f = \delta\tau_t^h$, leads to higher demand sensitivity of the general price level P_t, even without involving wages.

4.3. Methodology of Analysis

This section analyzes the impact of recent intensification of labor supply constraints on Japan's inflation dynamics using the following two-step approach.

Step 1: Estimate a linear model to obtain estimates of τ_t^h *and* τ_t^f

First, we perform a linear approximation around the steady state and conduct Bayesian estimation (see Appendix 2 for estimation details). This requires an observed series for either τ_t^h or τ_t^f. Here, we use the percentage of firms reporting "shortages" with respect to their employees in the *Tankan* survey, $\tau_t^{f,obs}$, as an observation for τ_t^f. Specifically, we set the observation equation for τ_t^f as follows.

$$\tau_t^f = c^\tau \tau_t^{f,obs},$$

where $c^\tau \in [0,1]$. That is, we assume that firms facing supply constraints in the model are a subset of those reporting labor shortages in the *Tankan* survey. If c^τ is close to zero, τ_t^f and τ_t^h become nearly zero over time. This formulation does not rule out the possibility

[17] Taking the logarithm of both sides of Equation (8) and differentiating with respect to the demand shock $\log d_t$ we can confirm $\frac{\partial \log \bar{P}_t}{\partial \log d_t} = \frac{\partial \log P_t}{\partial \log d_t} + \lambda_t^p \frac{\partial \log Y_t}{\partial \log d_t} > \frac{\partial \log P_t}{\partial \log d_t}$.

that the labor supply constraint assumed in the model is uninformative for explaining the data. τ_t^h is determined from its proportional relationship with τ_t^f (Equation (4)).

In the estimation, τ_t^h and τ_t^f will be identified as follows. First, in the linear approximation model, an increase in τ_t^h has an effect similar to an increase in the wage markup. This occurs because the nominal wage of households under constraints, $\overline{W}_t$, becomes higher than the aggregate nominal wage due to a premium arising from the constraint. That is, an increase in τ_t^h leads to an increase in nominal wages independently of the marginal rate of substitution between consumption and labor due to its composition effect. Similarly, an increase in τ_t^f has an effect analogous to an increase in price markups. This occurs because the nominal price of firms under constraints, $\bar{P}_t$, becomes higher than the aggregate price level due to a constraint-induced premium. That is, an increase in τ_t^f leads to higher prices through a composition effect independently of marginal costs.

Given this, τ_t^h and τ_t^f will be estimated based on the extent to which the proportion of firms reporting labor shortages correlates with wage fluctuations not explained by the marginal rate of substitution between consumption and labor, and with price fluctuations not explained by marginal costs.

Step 2: Evaluating the Impact of Labor Supply Constraints on Inflation Dynamics via "Comparative Static Analysis"

In the linear model estimated in Step 1, the effects of τ_t^h and τ_t^f on the slope of the Phillips curve (the relationship between aggregate demand and inflation rate) are evaluated at the steady-state values of these variables, τ^h and τ^f. In Step 2, we analyze how much the demand sensitivity of inflation increases when these parameter values are replaced with the estimates of τ_t^h and τ_t^f for the most recent quarter.

4.4. Estimation Results

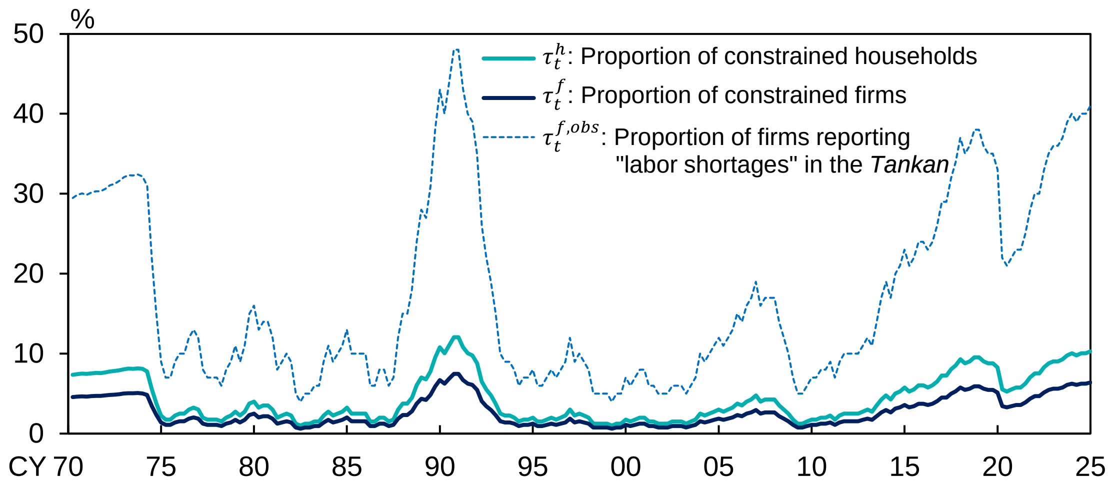
Estimates of τ_t^h and τ_t^f

First, we look at the estimates of τ_t^h and τ_t^f in the Step 1 (Figure 12).

The estimated values of τ_t^h and τ_t^f have risen to considerable levels during the bubble period and since the mid-2010s[18]. For example, in the most recent quarter (2025/Q1), the estimated results indicate that approximately 10% of households and about 6.5% of firms faced supply constraints in the model. Conversely, during the late 1990s to early 2000s, the estimated values of τ_t^h and τ_t^f were close to zero, suggesting that labor supply constraints had no effect.

[18] Note that the marginal likelihood of the estimated model is higher than when we assume $c^\tau = 0$.

(Figure 12) Estimates of τ_t^h and τ_t^f



Note: Figures for τ_t^h, proportion of households under constraints, and those for τ_t^f, proportion of firms under constraints, are posterior means.

Impact of Recent Intensification of Labor Supply Constraints on Inflation Dynamics

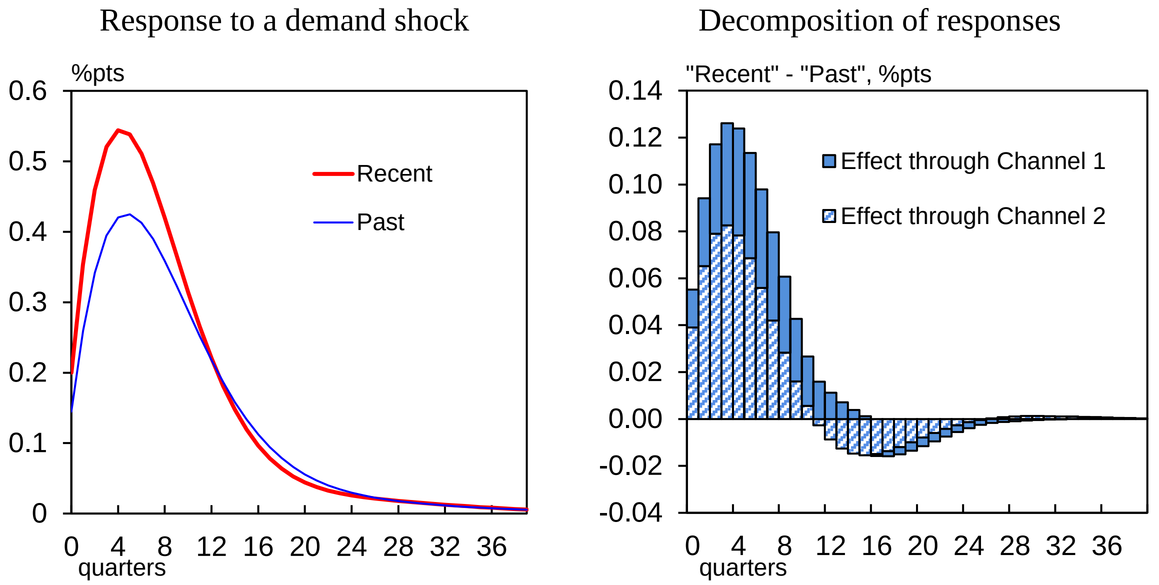
Next, we present the results of Step 2. Specifically, we compare the impulse responses of the inflation rate to a demand shock (preference shock) when the parameters τ^h and τ^f are replaced with: (1) the estimated values of τ_t^h and τ_t^f for the most recent period (2025/Q1), and (2) the average values of τ_t^h and τ_t^f from periods when labor supply constraints were not intense (periods excluding early 1970s, the bubble period, and 2014 onwards).

The left panel of Figure 13 suggests that the recent intensification of labor supply constraints has clearly strengthened the inflation response to demand shocks. Specifically, at the peak of the impulse response, the inflation rate's reaction is stronger by nearly 30%. The right panel of Figure 13 decomposes the difference in these impulse responses into the impact through Channel 1 (an increase in constrained households) and Channel 2 (an increase in constrained firms). It suggests that the effect through both channels contributes to the amplification of price fluctuations.

Figure 14 shows the slope of the Phillips curve. Specifically, it plots the relationship between real GDP and inflation rate when demand-side shocks (preference shocks and monetary policy shocks) are randomly generated. This figure more directly suggests that the recent intensification of labor supply constraints has steepened the Phillips curve[19].

[19] Note that in Figure 14, since the parameter τ^h is assumed constant in the simulation, the slope of "Recent" is steeper than that of "Past" even when the aggregate demand stagnates (i.e., the region where the horizontal axis is negative).

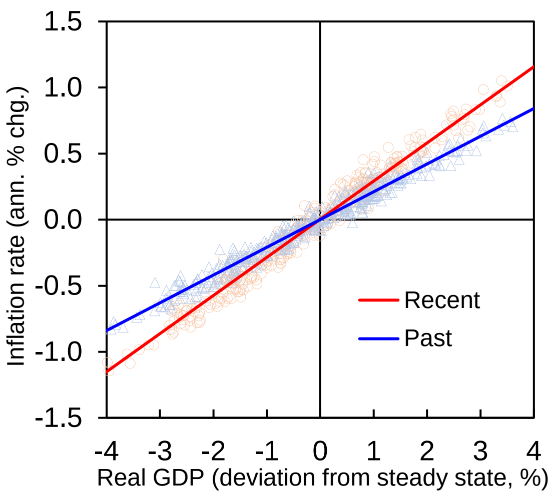
(Figure 13) Impulse Response of the Inflation Rate



Notes: 1. The left panel shows the impulse response of the inflation rate to +1 standard deviation preference shock. "Recent" refers to parameters τ^h and τ^f set to the values of τ_t^h and τ_t^f in 2025/Q1 (0.103 and 0.064, respectively), and "Past" represents the case where τ^h and τ^f are set to their historical averages (excluding the early 1970s, the bubble period, and 2014 onwards) of τ_t^h and τ_t^f (0.023 and 0.014, respectively).

2. The right panel shows the decomposition of the difference in impulse responses in the left panel. The difference in impulse responses when τ^f is fixed at the "Past" value (0.014) is calculated as the "Effect through Channel 1," while the remainder is calculated as the "Effect through Channel 2."

(Figure 14) Relationship between Inflation Rate and Aggregate Demand



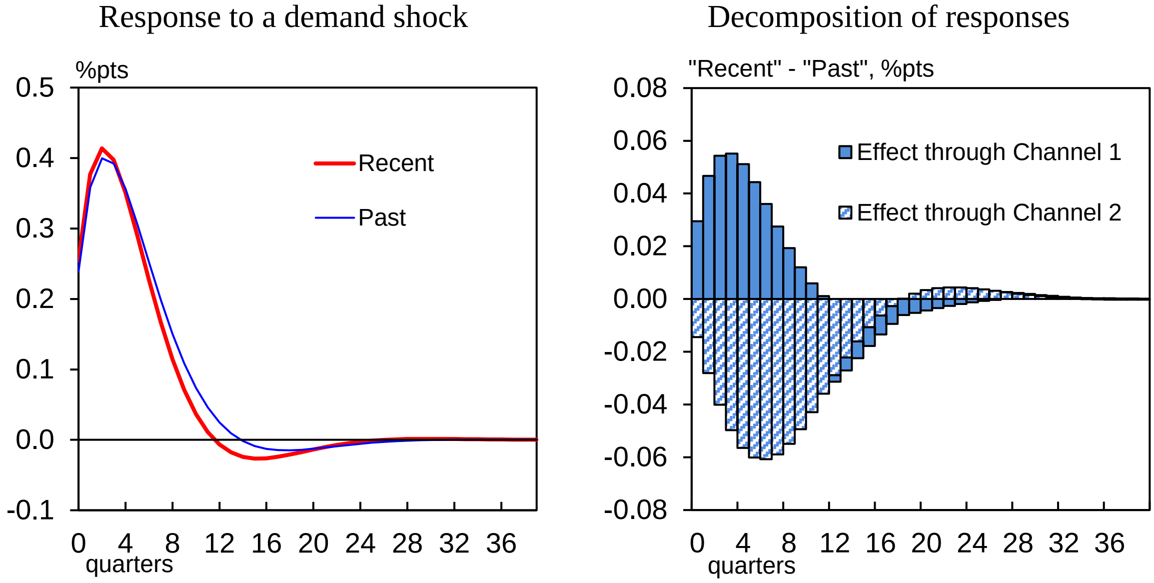
Note: This plot shows the inflation rate and real GDP when demand-side shocks (preference shock and monetary policy shock) are randomly generated over 400 periods, where the lagged inflation rate is controlled.

Interestingly, the impulse responses of real wages to demand shocks in Figure 15 suggest that the recent intensification of labor supply constraints may not have led to an increase in the demand sensitivity of real wages[20]. Considering the background, an increase in

[20] The coexistence of tight labor market and stagnant real wages has been observed in the post-pandemic United States. Some studies interpreted this phenomenon through mechanisms different from those discussed

constrained households (an increase in τ_t^h) strengthens the response of nominal wages to demand shocks, thereby increasing the demand sensitivity of real wages. On the other hand, an increase in constrained firms (an increase in τ_t^f) strengthens the price response to demand shocks directly without involving nominal wages, thereby reducing the demand sensitivity of real wages. The estimation result suggests that these opposing effects have roughly offset each other in Japan's past data.

(Figure 15) Impulse Response of Real Wages



Notes: 1. The left panel shows the impulse response of the real wages to +1 standard deviation preference shock. "Recent" refers to parameters τ^h and τ^f set to the values of τ_t^h and τ_t^f in 2025/Q1 (0.103 and 0.064, respectively), and "Past" represents the case where τ^h and τ^f are set to their historical averages (excluding the early 1970s, the bubble period, and 2014 onwards) of τ_t^h and τ_t^f (0.023 and 0.014, respectively).

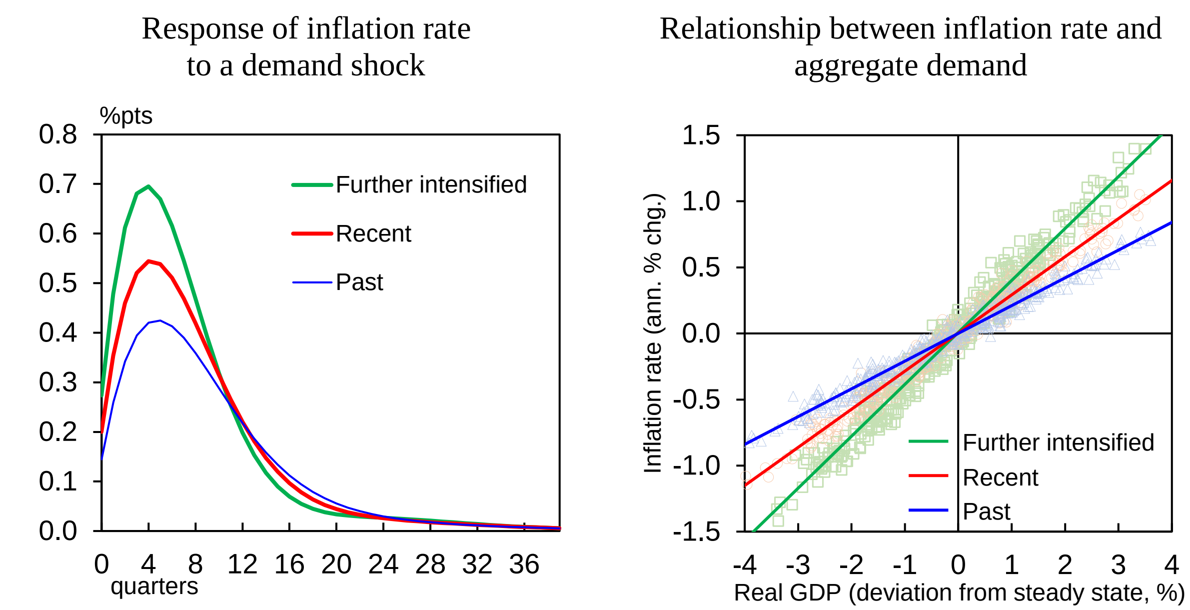
2. The right panel shows the decomposition of the difference in impulse responses in the left panel. The difference in impulse responses when τ^f is fixed at the "Past" value (0.014) is calculated as the "Effect through Channel 1," while the remainder is calculated as the "Effect through Channel 2."

Implications for the Outlook

In the future, if population aging and declining birthrate continue to progress, further intensification of labor supply constraints is expected to lead to greater price fluctuations in response to changes in aggregate demand. For example, if the proportion of firms facing constraints were to double from 6.5% to 13%, the responsiveness of inflation to aggregate demand fluctuations would increase accordingly (Figure 16).

in this paper. For example, Afrouzi et al. (2025) theoretically demonstrate a mechanism where unexpected price increases cause real wages to fall. This decline, by stimulating workers' job search activity, leads firms to intensify their hiring efforts, shifting the Beveridge curve upward. They argue that this theory is consistent with the observation in the United States for the Beveridge ratio to rise during periods of high inflation stemming from negative supply shocks.

(Figure 16) Scenario of Further Intensification of Labor Supply Constraints



Notes: 1. The left panel shows the impulse response of the inflation rate to +1 standard deviation preference shock. "Recent" refers to parameters τ^h and τ^f set to the values of τ_t^h and τ_t^f in 2025/Q1 (0.103 and 0.064, respectively), "Past" represents the case where τ^h and τ^f are set to their historical averages (excluding the early 1970s, the bubble period, and 2014 onwards) of τ_t^h and τ_t^f (0.023 and 0.014, respectively) , and "Further intensified" represents the case where τ^h and τ^f are doubled from those of "Recent" (0.206 and 0.127, respectively).

2. The right panel plots the inflation rate and real GDP when demand-side shocks (preference shock and monetary policy shock) are randomly generated over 400 periods, where the lagged inflation rate is controlled.

5. Measures to Counter Supply Constraints

This section begins by reviewing recent discussions on responses to supply constraints to examine potential countermeasures that could mitigate the risks and impacts of future supply constraints, as suggested by the analysis in the preceding section. Then, it provides an overview of various supply constraint episodes in Japan and analyzes how Japanese firms responded to these constraints. Finally, the section discusses the effectiveness of these countermeasures using the DSGE model from the previous section.

5.1. Recent Discussions on Measures to Counter Supply Constraints

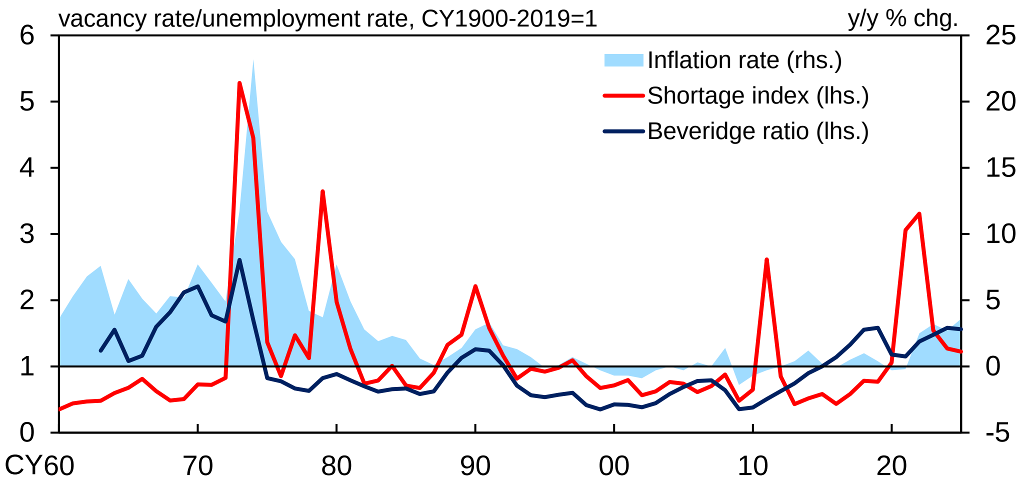
Recent studies have discussed measures to mitigate the risks and impacts of supply constraints. From the perspective of securing stable production factors, strategies include increasing material inventories (Lücker et al., 2021) and diversifying suppliers (Todo et al., 2023). On the labor side, facilitating labor mobility has been highlighted as important, such as reducing mismatches through reskilling (Groiss and Sondermann, 2024).

On the other hand, to curb demand for constrained production factors, enhancing productivity and technological progress are highlighted as effective approaches. For instance, Parast (2020) empirically demonstrates that R&D investment contributes to supply chain resilience. Relatedly, AI implementation is expected to facilitate supply chain visualization and vulnerability identification (Zamani et al., 2023), and to complement or replace labor in various fields with robots, (Ni and Obashi, 2021; Kanazawa et al., 2025; Morikawa, 2025) [21].

5.2. Japan's Experience with Supply Constraints and its Responses

Throughout the history of Japan's economy, there has been supply constraints across various production factors. Figure 17 shows various indicators representing the degree of supply constraints over long-term time series. The shortage index for Japan, constructed by Caldara et al. (2025) rose significantly following the oil shocks of 1973 and 1979 and the 2011 Great East Japan Earthquake, indicating that supply constraints on energy and intermediate goods intensified during these periods. Furthermore, the Beveridge ratio (vacancy rate / unemployment rate) exceeded 1 and rose during the 1960s, suggesting that labor supply constraints intensified during that phase.

(Figure 17) Degree of Supply Constraint



Note: The shortage index for Japan is the percentage of articles in major U.S. newspapers that contain words indicating shortages, such as "shortage" or "bottleneck," related to energy, food, industry, or labor, out of the total number of articles that reference Japan or its major cities. Figures for the Beverage ratio from 2020 onwards are estimated based on vacancy rates from the Survey on Labour Economy Trend. The inflation rate is the CPI (all items). Figures for 2025 are January-June averages.
Sources: Caldara et al. (2025); Ministry of Health, Labour and Welfare; Ministry of Internal Affairs and Communications.

Therefore, we examine how firms responded to (1) the "(first) Lewis turning point" reached in the 1960s, (2) the two oil shocks of the 1970s, and (3) supply constraints arising

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[21] As Otaka and Kato (2025) argue, AI encompasses both technologies that substitute for labor and that complement labor. This contrasts with robots, which are often considered labor-substituting technologies (e.g., Berg et al., 2018).

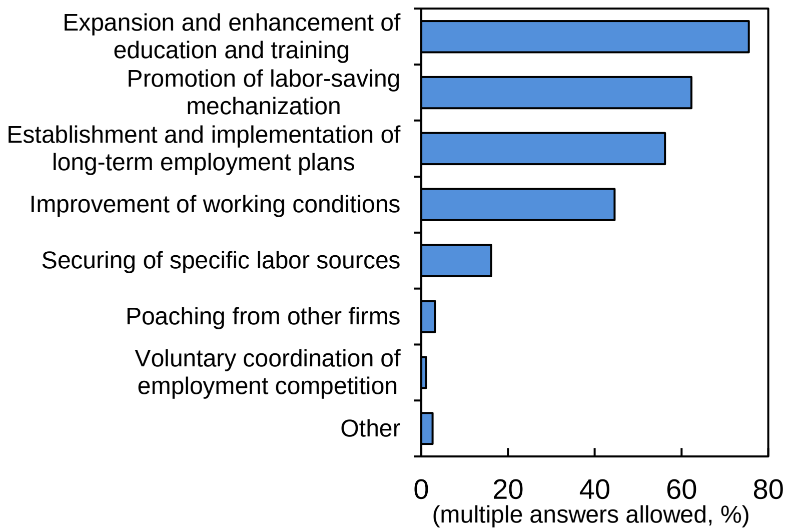
from the 2011 Great East Japan Earthquake and the 2011 Thailand floods.

1960s: First Lewis Turning Point

In Japan during the 1960s, the migration of young workers from rural to urban areas amid rapid economic growth depleted the so-called "unrestricted labor supply." Many view this period as Japan's economy reaching its "(first) Lewis turning point" (Minami, 1970), suggesting labor supply constraints had emerged.

Looking back at how firms responded to these labor supply constraints (Figure 18), in the short-run, wages for young workers were significantly raised, relative to other age groups, to secure labor. For instance, the development of wages for male manufacturing workers in the early 1960s shows that while wages for those aged 30 and over increased at an annual rate of around 5%, wages for those aged 19 and under increased at an annual rate exceeding 10%. However, by the late 1960s, labor-saving initiatives, such as capital investment aimed at addressing labor shortages in the long-run (labor-saving investment) and productivity enhancements through education and training (human capital investment), had progressed. Consequently, the situation in which wage growth for young workers had been significantly higher was resolved[22].

(Figure 18) Measures to Counter Labor Shortages



Source: Japan Association of Corporate Executives (1963), "The Actual State of Management Decision-Making in Japanese Firms (IV): Changes in the Labor Market and Corporate Activities." (in Japanese)

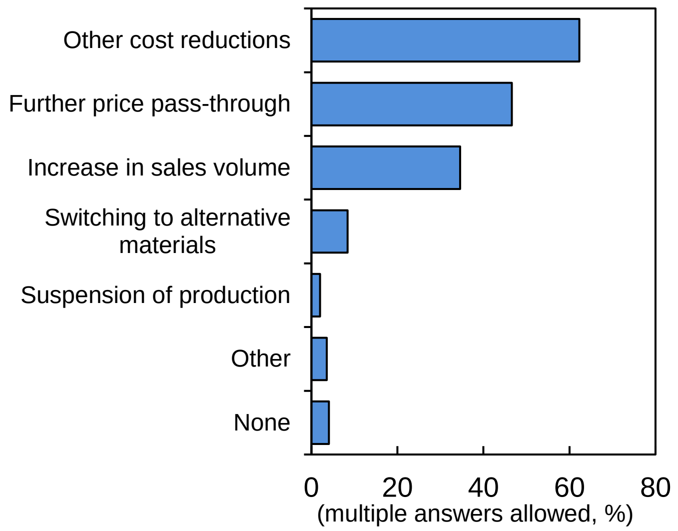
[22] For example, in the Development Bank of Japan's "Survey on Planned Capital Spending," the proportion of firms citing "labor shortages" as a motive for capital investment increased from 1967 to 1971.

1970s-1980s: Oil Shocks

Entering the 1970s, Japan faced two oil shocks caused by reduced and unstable crude oil supplies due to heightened tensions in the Middle East, leading to widespread energy supply constraints.

Faced with energy supply constraints, firms initially responded to rising costs from soaring crude oil prices by passing on price increases and cutting other costs (Figure 19). Furthermore, these price increases—though to varying degrees between the first and second oil shocks—were also reflected in wages. As a long-run response, amid the enactment of the 1979 Act on Rationalizing Energy Use, firms actively pursued energy conservation and alternative energy investments to reduce their dependence on crude oil by improving energy consumption per unit of output (Figure 20)[23].

(Figure 19) Response to Rising Oil Prices



Source: Economic Planning Agency (1980), "Survey on Corporate Behavior in Response to Changes in Domestic and Overseas Economic Environments." (in Japanese)

2010s: The 2011 Great East Japan Earthquake and the 2011 Thailand Floods

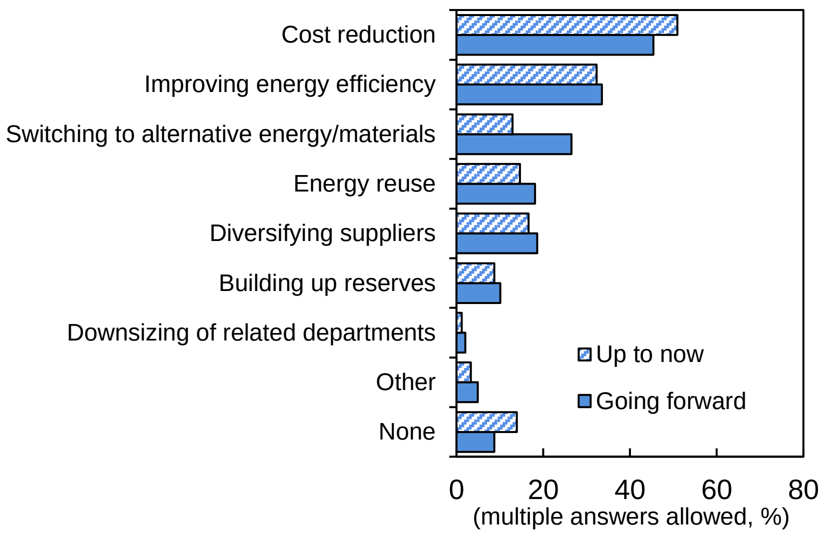
On entering the 2000s, supply chain disruptions occurred repeatedly both domestically and internationally due to natural disasters such as earthquakes and floods. Particularly in 2011, the Great East Japan Earthquake and major floods in Thailand caused disruptions in the supply of key components, leading to constraints in the supply of intermediate goods[24]. Furthermore, the Great East Japan Earthquake also resulted in energy supply constraints

[23] Nomura (2021) points out that during this period, energy-saving technologies were embodied in capital and available at low cost.

[24] Additionally, the 2007 Niigata Chuetsu-Oki Earthquake and the 2016 Kumamoto Earthquake also disrupted the supply of key components. Furthermore, in 2018, heavy rainfall resulting in floods in Western Japan caused disruptions to the logistics network.

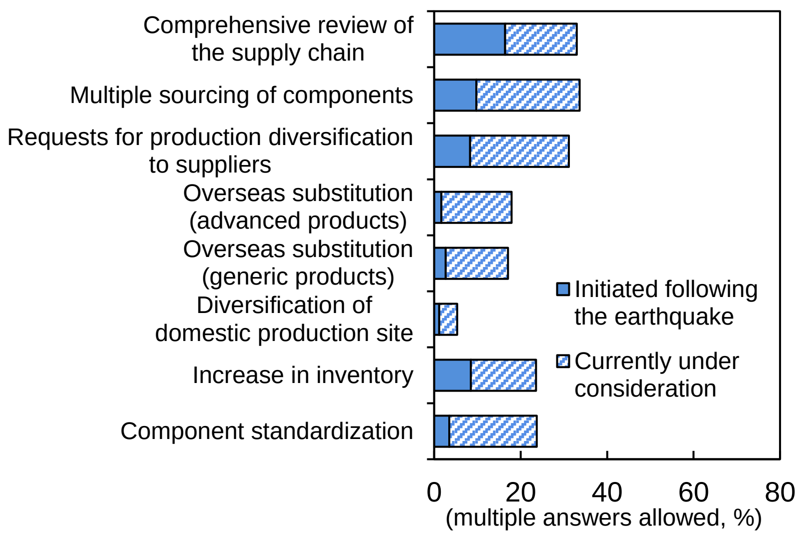
in the form of an unstable electricity supply due to the shutdown of nuclear power plants.

(Figure 20) Medium- to Long-Run Response to Oil Supply Concerns



Source: Economic Planning Agency (1980), "Survey on Corporate Behavior in Response to Changes in Domestic and Overseas Economic Environments." (in Japanese)

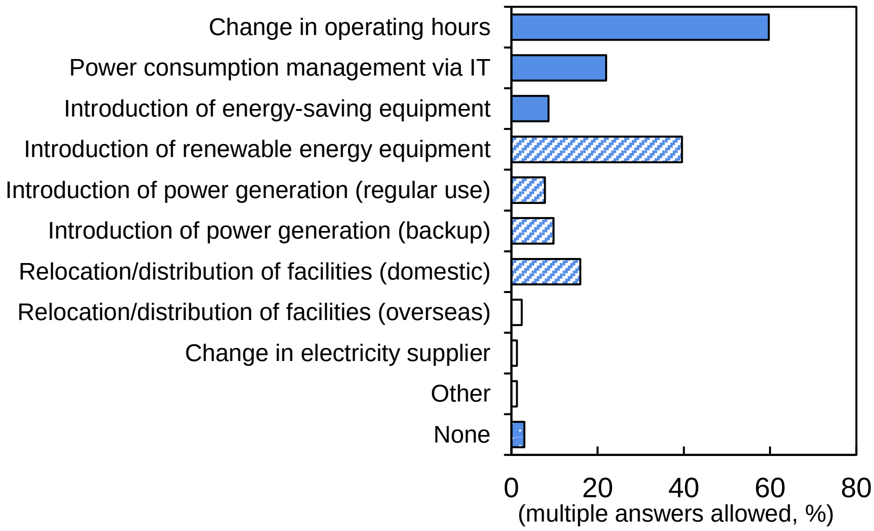
(Figure 21) Risk Diversification for Disasters



Source: Japan Bank for International Cooperation, "FY2011 Survey Report on Overseas Business Operations by Japanese Manufacturing Companies." (in Japanese)

Looking at how firms responded to intermediate goods supply constraints (Figure 21), immediately after the Great East Japan Earthquake, efforts focused on grasping the overall supply chain and increasing inventory levels. Subsequently, the long-run response involved supply chain restructuring, including expanding overseas production and procurement. This led to an increase in the import penetration ratio for capital and production goods. Furthermore, the emergence of electricity supply constraints prompted firms to conserve power and invest in energy-saving equipment (Figure 22). Note that the yen's appreciation during this period appears to have helped suppress short-term inflationary pressures stemming from supply constraints.

(Figure 22) Response to Power Supply Issues



Source: Development Bank of Japan, "Survey on Corporate Behavior (June 2012)." (in Japanese)

Technological Changes in Response to Supply Constraints

In summary, Japan's past experience with supply constraints suggests that while such constraints raise the prices of constrained production factors in the short-run, they also prompt firms to respond in the long-run with capital investments and productivity improvements aimed at reducing reliance on the constrained factor, by improving production efficiency or using alternative inputs.

To examine the macroeconomic impact of these long-term efforts of firms, we followed Jin and Jorgenson (2010) and applied a state space model—comprising a translog price function and share equations—to Japan's macroeconomic data to measure technological changes[25]. This approach is similar to that of Fukunaga and Osada (2009) and Aoki et al. (2023). However, whereas Fukunaga and Osada (2009) and others assumed three production factors: (1) capital, (2) labor, and (3) energy, this paper also considers (4) intermediate goods as production factors to capture substitution across a broader range of inputs[26].

[25] The share functions are derived as the partial derivative of the translog price function with respect to the factor price of each production factor ($lnP_{i,t}$), under the assumptions of perfect competition and constant returns to scale. Note that the price function under the Cobb-Douglas production function corresponds to setting $\beta_{i,j}$, $f_{i,t}$, and $f_{p,t}$ equal to zero in the translog price function.

[26] This classification of production factors is consistent with Jin and Jorgenson (2010).

$$lnP_{Qt} = \alpha_0 + \sum_i \alpha_i lnP_{i,t} + \frac{1}{2}\sum_{i,j} \beta_{i,j} lnP_{i,t} \cdot lnP_{j,t} + \sum_i lnP_{i,t} \cdot f_{i,t} + f_{p,t} + \varepsilon_t^p,$$

$$\nu_{i,t} = \alpha_i + \sum_j \beta_{i,j} lnP_{j,t} + f_{i,t} + \varepsilon_{i,t}^{v},$$

$$f_{p,t} - f_{p,t-1} = \gamma_p + \sum_i \gamma_{p,i}(f_{i,t-1} - f_{i,t-2}) + \gamma_{p,p}(f_{p,t-1} - f_{p,t-2}) + \varepsilon_{p,t}^f,$$

$$f_{i,t} - f_{i,t-1} = \gamma_i + \sum_j \gamma_{i,j}(f_{j,t-1} - f_{j,t-2}) + \gamma_{i,p}(f_{p,t-1} - f_{p,t-2}) + \varepsilon_{i,t}^f,$$

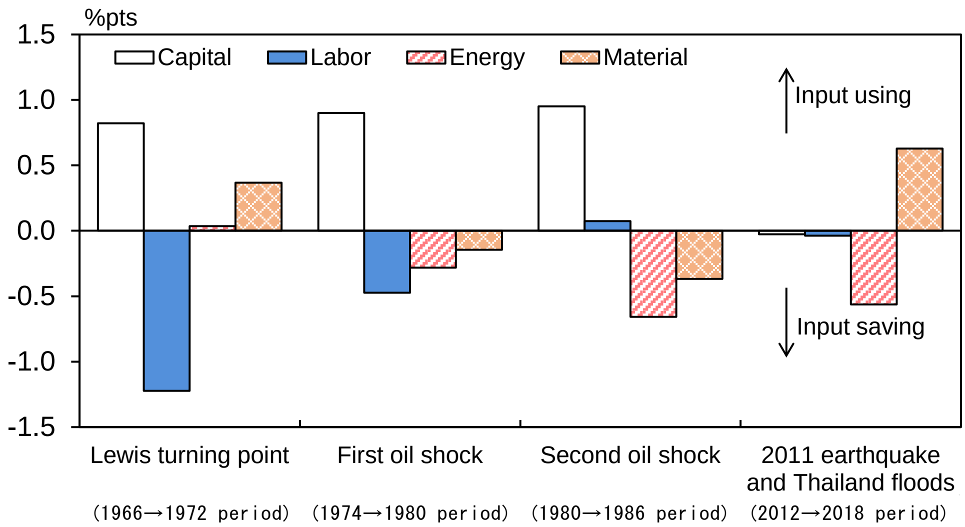
where P_{Qt} denotes the output price; $P_{i,t}$ denotes the input price of production factor i; i and j are production factors (i.e., capital, labor, energy, material); $\nu_{i,t}$, $f_{P,t}$, and $f_{i,t}$ denote the share of production factor i, the level of technology, and the bias of technological change regarding production factor i, respectively. $f_{i,t}$ represents the technological changes to increase or decrease the input quantity relative to other production factors (i.e., the share of production factor). In addition, $\beta_{i,j}$ represents the elasticity of share of production factor i with respect to changes in the factor price of production factor j ($P_{j,t}$).

Figure 23 illustrates the biases of the technological change for each production factor beginning in the year after the respective supply constraint emerges. The technological changes in each phase can be summarized as follows: First, in the 1960s, labor-saving and capital-intensive technological changes emerged amid labor-saving investments. Following the first and second oil shocks, energy-saving technological changes occurred thanks to energy-saving investments. After the Great East Japan Earthquake and the Thailand floods in 2011, energy-saving technological changes occurred alongside investments for reducing electricity use. Additionally, reflecting the expansion of overseas procurement and production, technological changes favoring the use of imported intermediate goods were promoted.

Based on these results, firms' responses to supply constraints, such as capital investment, likely led to long-term technological changes that save on constrained production factors. Furthermore, these technological changes seem to mitigate the upward pressure on inflation rates caused by supply constraints by reducing the input of production factors whose relative prices have risen, thereby lowering the production costs of goods and services[27].

[27] When considering the long-run impact of supply constraints on inflation rates, it is also important to consider the second-round effects on medium-to-long-term inflation expectations (see Section 3).

(Figure 23) Biases of Technological Change in Response to Supply Constraints



Note: Figures represent impacts of technological change on the share of each production factor over the six years following the year of the supply constraint, and are estimated using the methodology of Jin and Jorgenson (2010).

5.3. The Effectiveness of Countermeasures: Implications from DSGE Model

Here, we discuss the effectiveness of countermeasures against supply constraints from the perspective of mitigating the effects of labor supply constraints on inflation dynamics using the DSGE model constructed in the previous section.

Labor-Saving Technological Changes Through the Use of Robots and AI

First, we examine the implications of labor-saving technological changes achieved through the use of robots and AI. Following Berg et al. (2018), we introduce robots and AI, which substitute labor, into the previous section's model (see Appendix 2 for details). Specifically, we assume that firm $j \in [0,1]$ produces output by using labor ($L_t(j)$) as well as robots and AI ($Z_t(j)$) as follows:

$$Y_t(j) = A_t \left[\kappa Z_t(j)^{\frac{\phi-1}{\phi}} + (1-\kappa) L_t(j)^{\frac{\phi-1}{\phi}} \right]^{\frac{\phi}{\phi-1}},$$

where ϕ is the elasticity of substitution between labor and robots/AI, and is assumed to be greater than 1.

Under this framework, firms facing labor shortages, $j \in F^D$, can use robots and AI to compensate for labor scarcity, thereby preventing their supply curves from becoming perfectly vertical. Assuming that the nominal price ($\bar{P}_t$) of firms facing labor shortages, $j \in F^D$, follows Calvo-type pricing like other firms, they determine their prices by considering the following real marginal cost ($\overline{mc}_t$):

$$\overline{mc}_t = \frac{r_t^Z}{\kappa}\left(\frac{\bar{Z}_t}{\bar{Y}_t}\right)^{\frac{1}{\phi}}, \tag{11}$$

where $\bar{Z}_t$ and $\bar{Y}_t$ represent the real input of robots and AI and real output, respectively, of firms facing labor shortages, $j \in F^D$. r_t^Z is the real rental cost of robots and AI.

In this exercise, we examine the impact of an increase in the elasticity of substitution between labor and robot/AI, ϕ, as one type of labor-saving technological changes[28]. When aggregate demand increases, constrained firms cannot increase their labor input. Therefore, they are expected to respond to the increase in demand by increasing their use of robots and AI ($\bar{Z}_t$). As shown in Equation (11), when the elasticity of substitution, ϕ, is high, firms can use robots and AI without compromising production efficiency. Consequently, constrained firms' marginal costs are expected to rise less. Thus, the greater substitutability between labor and robots/AI would lead firms facing labor shortages to curb raising prices in response to increased aggregate demand (Figure 24). Based on these considerations, it can be concluded that, as labor-saving technological progress advances, firms' pricing behavior becomes less susceptible to the impact of intensifying labor supply constraints.

Facilitating Labor Mobility through Reskilling, etc.

Finally, as noted in recent studies such as Groiss and Sondermann (2024), we briefly examine the implications of facilitating labor mobility through reskilling, etc. Even if constraints on households' labor supply intensify, these constraints are less likely to spread to firms if labor can be efficiently utilized across the entire economy. The DSGE model, constructed in the previous section, involves this concept as the parameter δ (see Equation (4)). This parameter represents labor market mobility as it determines the extent to which workers can be reallocated from areas with labor surpluses to areas with labor shortages.

In this model, the labor market is the most flexible when $\delta = 0$. Figure 25 shows the impulse response of the inflation rate to demand shocks when the value of δ changes from its posterior mean of 0.62 to 0. The figure suggests that policies that boost labor market mobility, such as through reskilling, could mitigate the impact of intensified labor supply constraints to a certain degree.

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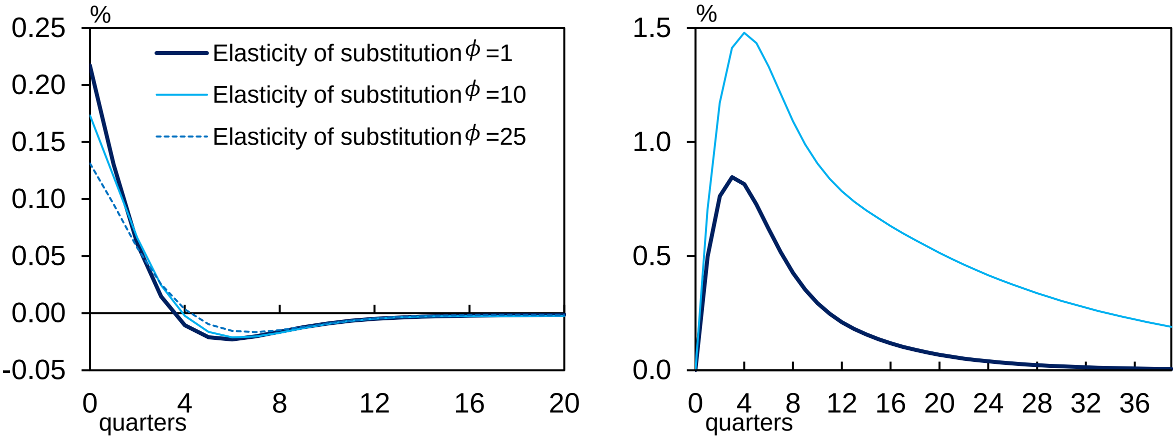
[28] In recent years, software investment has been increasing amid the growing adoption of labor-saving technologies such as touch panels, particularly in the non-manufacturing sector where labor shortages have become increasingly severe.

(Figure 24) Impact of Labor-Substituting Technologies (Robots and AI)

Price response of firms facing labor shortages to a demand increase

Response of robot and AI capitals to a demand increase

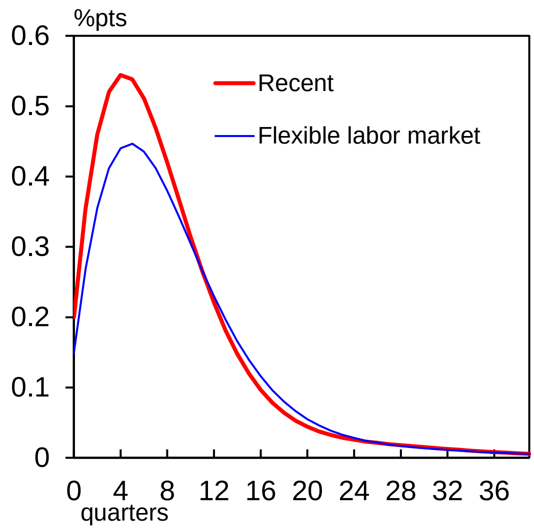


Notes: 1. The impulse responses of $\bar{p}_t$ (left panel) and Z_t (right panel) to an increase in aggregate demand (one standard deviation interest rate cut shock) are shown when the elasticity of substitution between labor and robots/AI, ϕ, changes. The parameters τ^h and τ^f, which represent the degree of labor supply constraints, are set to the estimated 2025/Q1 values of τ_t^h and τ_t^f (0.103 and 0.064, respectively). In addition, to avoid counterintuitive results (e.g., decreased demand for constrained firms), the value of the Calvo parameter for prices (ξ_p) is set to 0.53.

2. Figures are deviations from the steady state levels.

(Figure 25) Impact of Labor Market Mobility

Response of the inflation rate to a demand increase



Note: The figure shows the impulse response of the inflation rate to +1 standard deviation preference shock. "Recent" represents the case where parameters τ^h and τ^f are set to their values at 2025/Q1 (0.103 and 0.064, respectively). "Flexible labor market" represents the case where $\delta = 0$, namely, parameters τ^h and τ^f are set to 0.103 and 0.000, respectively.

6. Conclusion

This paper analyzes the impact of supply constraints on inflation dynamics and its mechanisms from empirical and theoretical perspectives. It then goes on to examine recent changes in the relationship between supply constraints and inflation dynamics, as well as measures to mitigate the effects of supply constraints on inflation.

The results of the analysis suggest that the intensification of supply constraints has impacted Japan's inflation dynamics through the following channels. First, intensifying supply constraints on labor and materials had a persistent impact on the inflation rates. Second, intensification of labor supply constraints contributed to recent inflation increases by heightening the sensitivity of inflation rates to demand fluctuations (i.e., nonlinearity). The results suggest that persistent supply constraints, under accommodative financial conditions, also led to a recent rise in inflation expectations.

Furthermore, the analysis implies that inflationary pressures arising from intensifying supply constraints have become more frequent and significant in recent years. Looking ahead, the further intensification of labor supply constraints could strengthen inflationary pressures in a nonlinear manner. As highlighted by the model simulation, achieving technological progress through firm-based initiatives and government policies (e.g., AI adoption), along with facilitating inter-industry and inter-firm labor mobility, are important for easing supply constraints in Japan.

It should be noted, however, that much of the sample period analyzed in this study falls within a time frame without notable price increases. Potential improvements of the model include refining the identification of supply constraints by introducing narrative sign restrictions into the structural VAR model. One of the key challenges for the DSGE model is to refine the determination of wages for workers under supply constraints by incorporating search and matching mechanisms, as well as elements of labor market monopsony. Deepening the analysis of the relationship between supply-side factors and inflation dynamics will require further refinement of the model and the collection of more data to support it.

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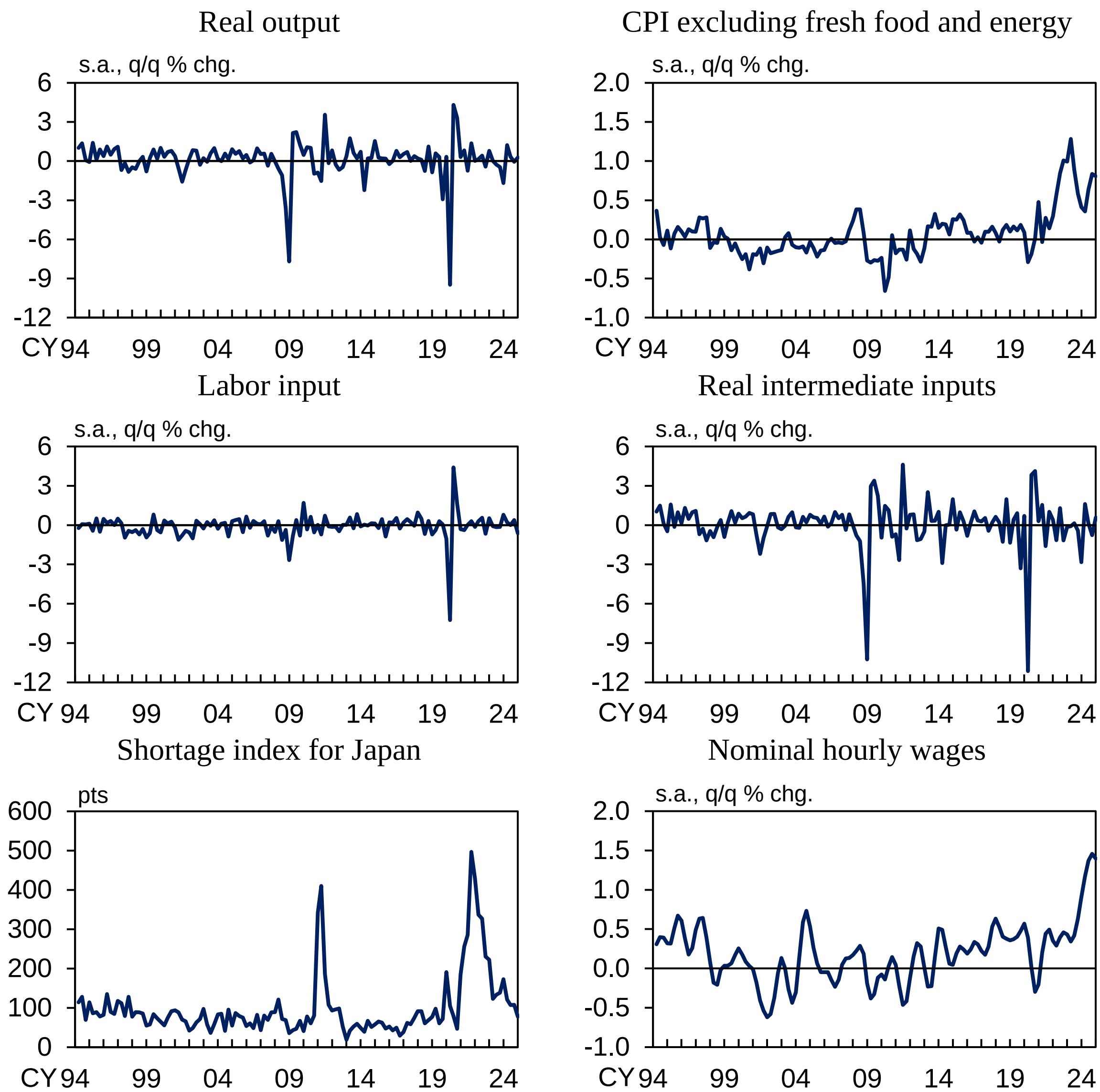
Appendix 1. Estimation of SVAR Model and Robustness Checks

1.1. Details of Estimation

The data used for estimating the SVAR model in Section 3 is shown in Figure A1.

(Figure A1-1) Data Used for Estimation

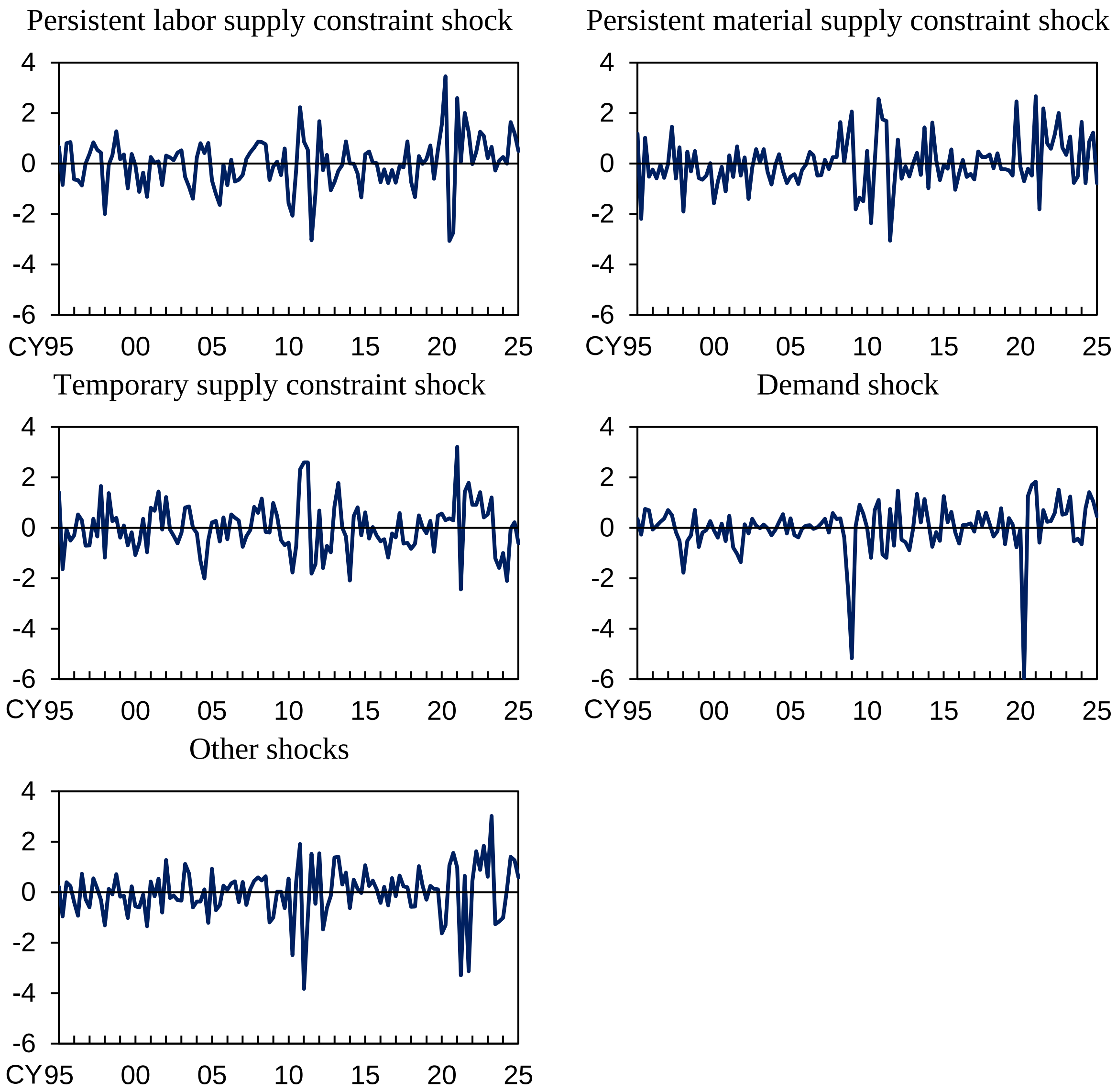


Note: CPI (excluding fresh food and energy) excludes the reduction in mobile phone charges and the effects of the consumption tax hikes. Labor input is calculated by multiplying the number of employed persons from the Labor Force Survey by the total working hours from the Monthly Labor Survey. Real intermediate inputs are calculated as the difference between real output and real value added in the QNA. The shortage index for Japan is the percentage of articles in major U.S. newspapers that contain words indicating shortages, such as "shortage" or "bottleneck," related to energy, food, industry, or labor, out of the total number of articles while focusing on articles containing the name of the country or major cities in Japan. Nominal hourly wages are calculated by dividing the total cash earnings by total working hours from the Monthly Labor Survey. Similar to Nakamura et al. (2024), nominal hourly wages are the trend-cycle components of the X-12 ARIMA model, and exclude the effects of part-time worker ratio fluctuations.

Sources: Cabinet Office; Ministry of Internal Affairs and Communications; Ministry of Health, Labour and Welfare; Caldara et al. (2025).

Structural shocks identified by the SVAR model estimated using these data are as shown in Figure A1-2.

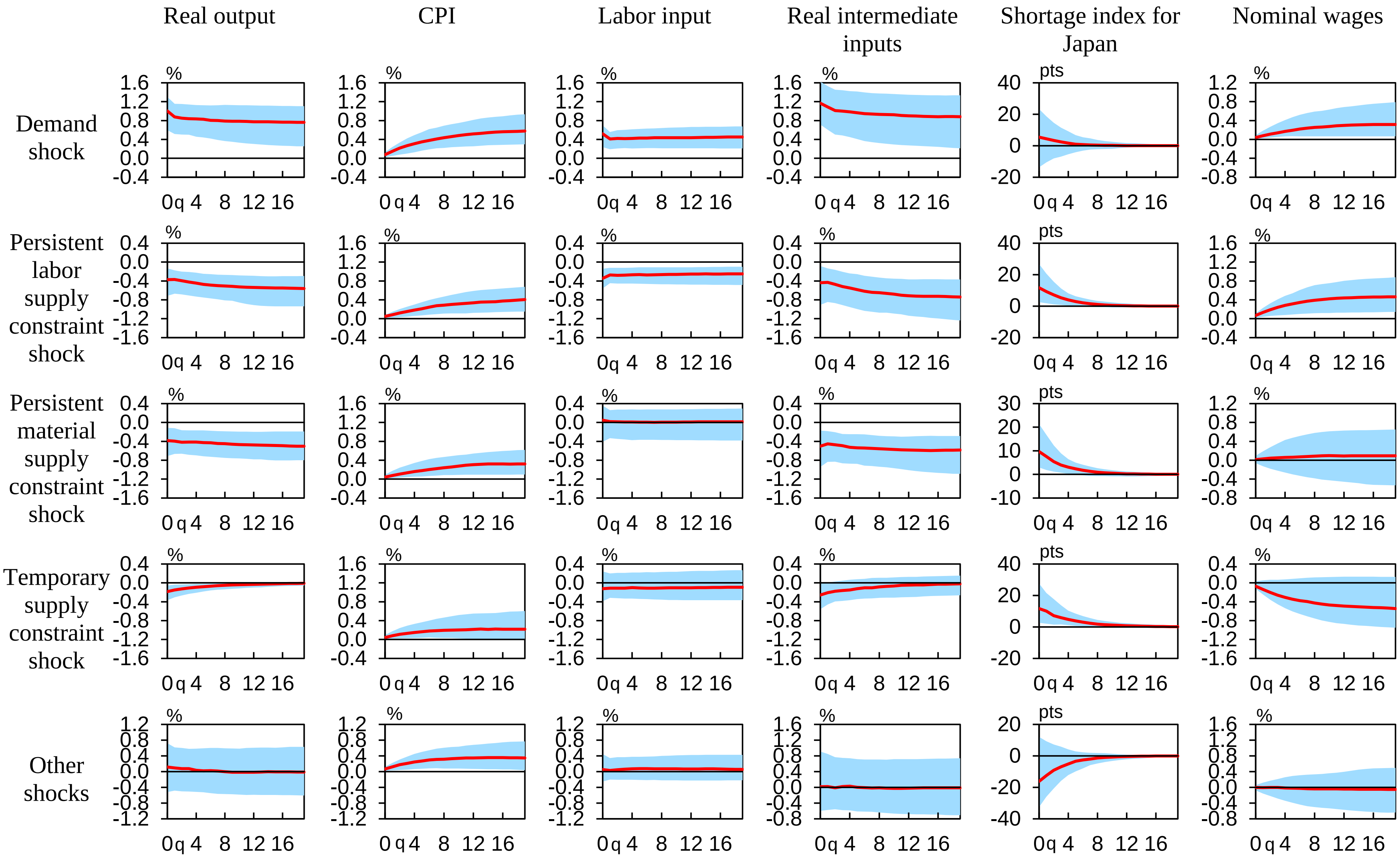
(Figure A1-2) Identified Structural Shocks



Note: Figures are averages of identified structural shocks.

Figure A1-3 also shows the impulse responses of all endogenous variables to these structural shocks.

(Figure A1-3) Impulse Responses



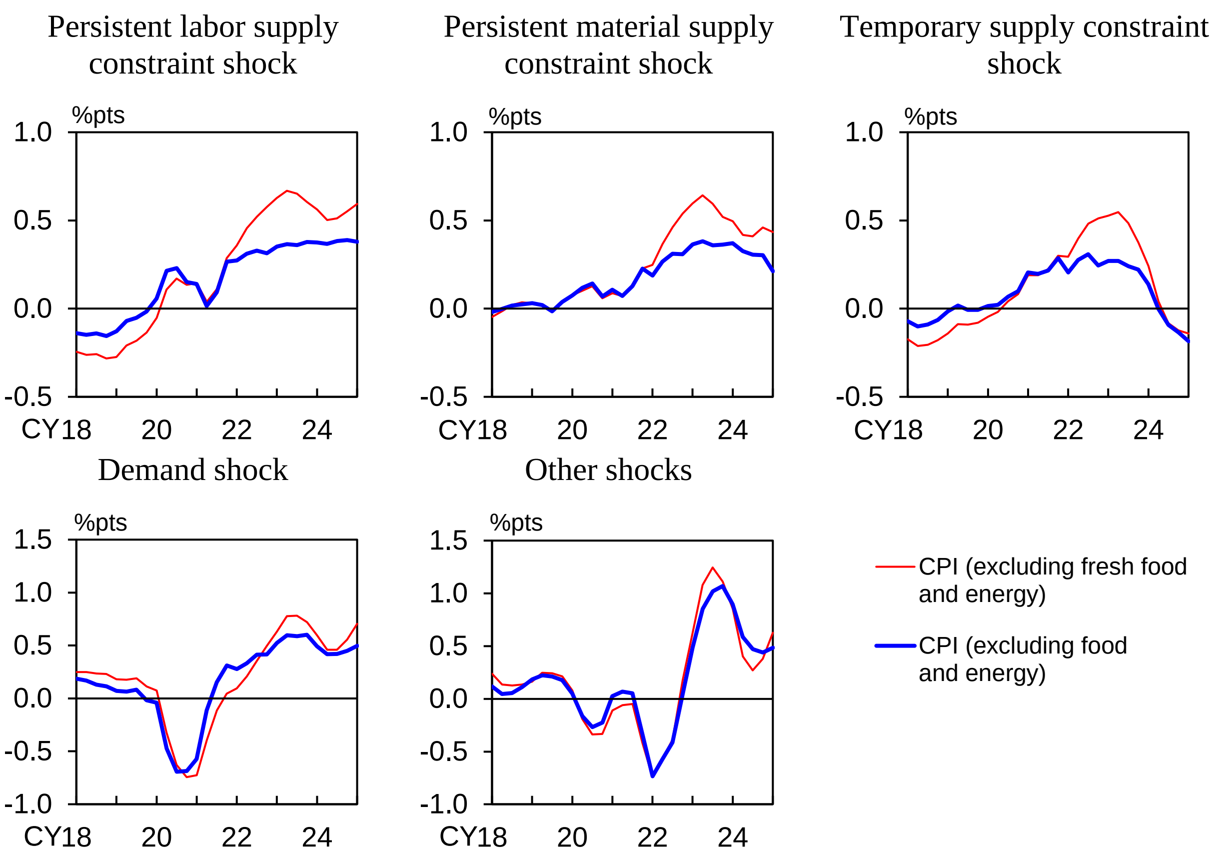
Note: Impulse responses of each variable to one standard deviation shock (cumulative logarithmic difference except for the shortage index). The shock occurs at period 0. The solid lines indicate the medians, while the shaded areas represent the 16th to 84th percentile ranges.

1.2. Robustness Checks

We assess the robustness of the SVAR model presented in Section 3. Specifically, we examine how the estimation results change when: (1) the inflation rate is replaced with the CPI excluding food and energy, and (2) the shortage index is replaced with the index created using Google Trends data. We also examine (3) the interpretability of the results when using U.S. data to confirm identification robustness.

First, Figure A1-4 shows the results of the historical decomposition when the inflation rate is replaced with the CPI (excluding food and energy). Even after changing the inflation rate data, the trends in the contributions of each shock to the inflation rate remain largely similar.

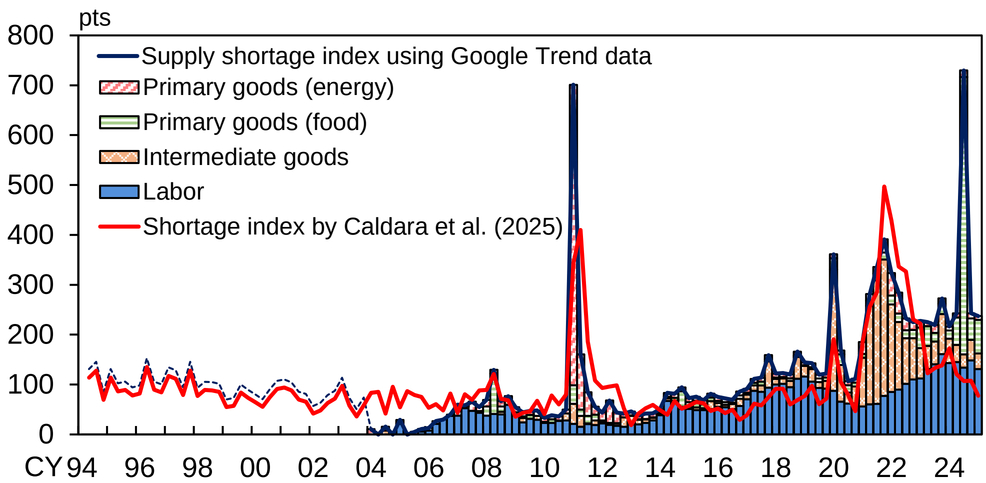
(Figure A1-4) Contributions of Each Shock to the CPI Inflation Rate (1)



Next, we examine the estimation results when the supply shortage index is changed from the shortage index constructed by Caldara et al. (2025) to the index constructed using Google Trends data. For each year from 2004 to 2025, we extracted supply-related search terms (e.g., "labor shortage") from the top search keywords related to "shortage" on Google in Japanese, and then we aggregated their search volumes to compile the index[1].

Figure A1-5 shows the trend of the supply shortage index constructed from Google Trends data. Similar to Figure 1, the index is broken down into components: (1) energy, (2) food, (3) industry, and (4) labor, based on the search terms. The trend generally follows that of the shortage index by Caldara et al. (2025), though a notable difference is the stronger impact of rice shortages observed from 2024 onwards.

(Figure A1-5) Supply Shortage Index Constructed using Google Trends Data



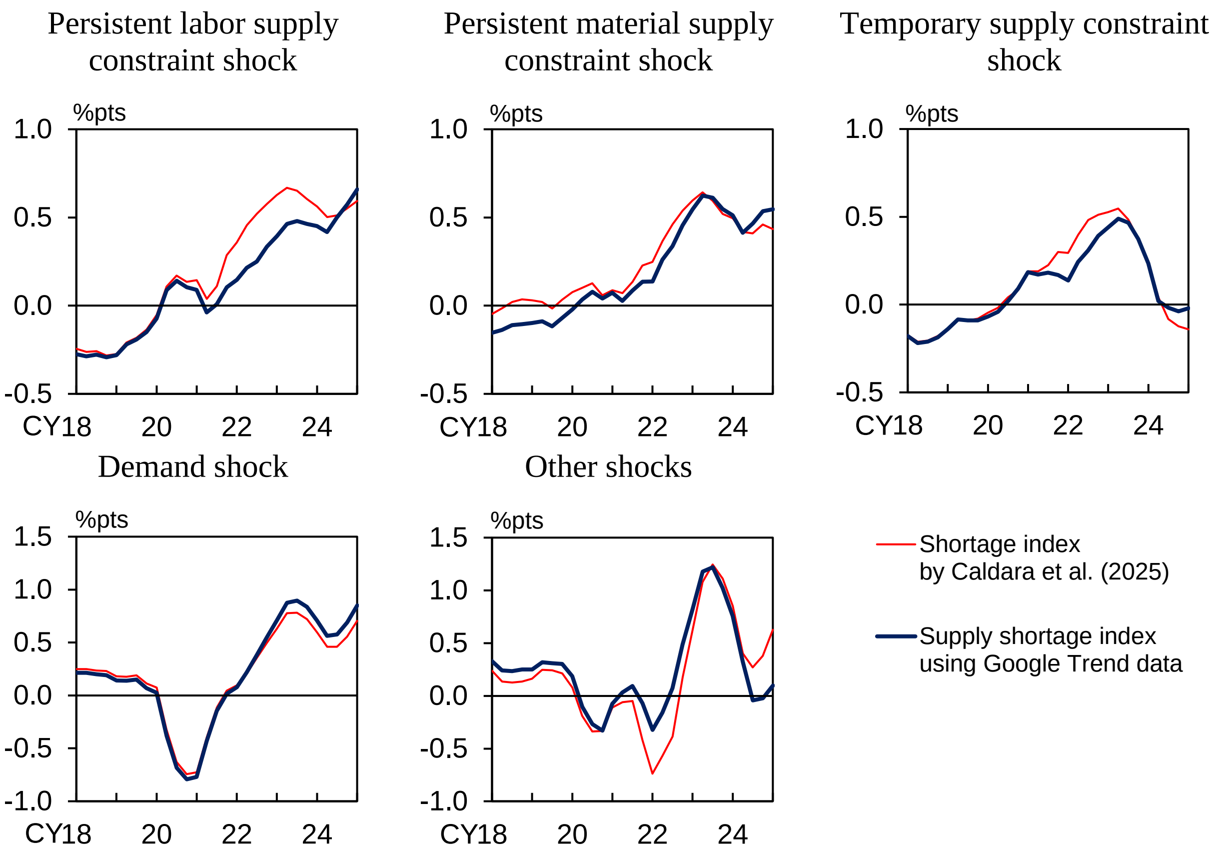
Notes: 1. The supply shortage index using Google Trends data represents the search volume of 42 supply-related keywords, such as "power shortage," "rice shortage," "semiconductor shortage," and "labor shortage," that ranked among the top search terms associated with "shortage" on Google each year from 2004 to 2025. The shortage index from Caldara et al. (2025) is the percentage of articles in major U.S. newspapers that contain words indicating shortages, such as "shortage" or "bottleneck," related to energy, food, industry, or labor, out of the total number of articles while focusing on articles containing the name of the country or major cities in Japan.
2. Prior to 2003, figures for the supply shortage index using Google Trend data are estimated using the shortage index from Caldara et al. (2025).

Sources: Caldara et al. (2025); Google Trends.

Figure A1-6 shows the results of the historical decomposition when the shortage index is replaced with the index constructed using the Google Trends data. Because the contribution of each shock to the inflation rate remains largely unchanged before and after the index change, the analysis results in this paper are considered robust with respect to the method used to construct the supply shortage index.

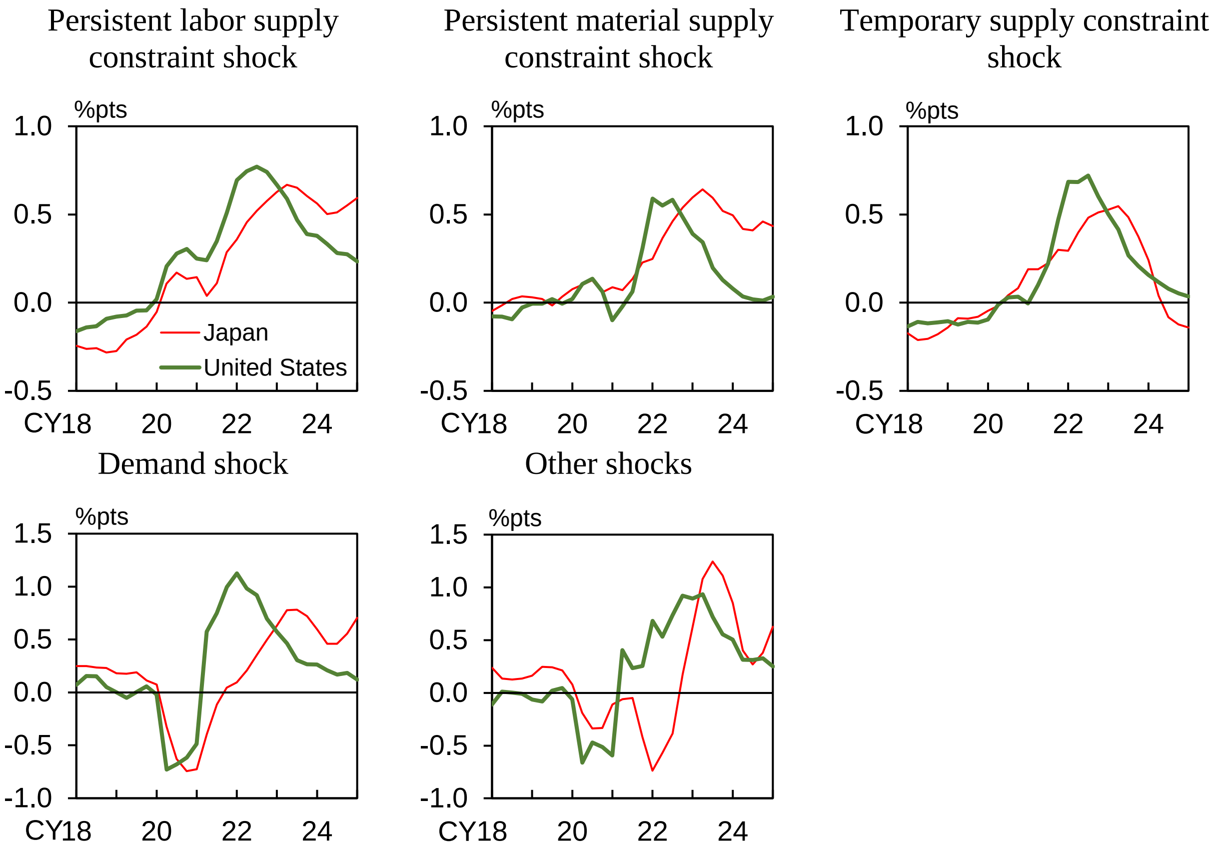
[1] Bernanke and Blanchard (2025) and Nakamura et al. (2024), who applied their model to Japan, use the number of Google searches for "shortage" as an indicator of the degree of supply constraints in the supply chain.

(Figure A1-6) Contributions of Each Shock to the CPI Inflation Rate (2)



Finally, Figure A1-7 presents the historical decomposition estimated using the U.S. data to assess the robustness of the identification. These results support prior research findings on high inflation in the United States following the pandemic. Specifically, examining the contribution of the demand shock confirms that large-scale fiscal policy generated significant inflationary pressure from the demand side after the pandemic. As the economy rapidly normalized, inflationary pressures intensified due to temporary and persistent supply constraints. This reflects delayed labor market reentry due to factors such as fiscal support in the form of benefit payments and shifts in worker preferences.

(Figure A1-7) Contributions of Each Shock to the U.S. CPI Inflation Rate



Appendix 2. DSGE Model

2.1. Details of Model

Household

Household $i \in [0,1]$ solves the following utility maximization problem to determine real consumption $C_t(i)$ and nominal bond holdings $B_t(i)$.

$$\max_{C_t(i),B_t(i)} \mathrm{E}_0 \sum_{t=0}^{\infty} \beta^t d_t \left[\frac{C_t(i)^{1-\sigma}}{1-\sigma} - \chi \frac{L_t(i)^{1+\eta}}{1+\eta}\right],$$

$$\text{s.t. } C_t(i) + \frac{B_t(i)}{P_t} + T_t = \frac{W_t(i)}{P_t} L_t(i) + R_{t-1}\frac{B_{t-1}(i)}{P_t} + D_t,$$

where P_t denotes the price level, T_t denotes the real lump-sum tax, $W_t(i)$ and $L_t(i)$ denote the nominal wage and labor supply of household i, R_t denotes the gross nominal interest rate, and D_t denotes real dividend income (firms' profits). d_t represents a preference shock and follows the AR(1) process:

$$\log d_t = \rho_d \log d_{t-1} + \epsilon_t^d. \quad \text{(A1)}$$

The following equations are derived from the first order conditions.

$$1 = E_t \Lambda_{t,t+1} \frac{R_t}{\Pi_{t+1}}, \quad \text{(A2)}$$

$$\Lambda_{t,t+1} = \beta E_t \frac{d_{t+1}}{d_t}\left(\frac{C_{t+1}}{C_t}\right)^{-\sigma}, \quad \text{(A3)}$$

where $\Lambda_{t,t+1}$ is a stochastic discount factor. Consumption levels are identical for all households because we assume the existence of a complete insurance market.

Household $i \in [0,1]$ supplies differentiated labor $L_t(i)$. However, it is assumed that some households (i.e., $\tau_t^h \in [0,1]$) face labor supply constraints in period t. Specifically, the labor supply of these households is assumed to be fixed at $L_t(i) = \bar{L}$. Conversely, the remaining households, accounting for the proportion $1 - \tau_t^h$, are assumed to have no labor supply constraints and to elastically supply the quantity of labor demanded at their own set wage level.

The proportion of households facing labor supply constraints, τ_t^h, is assumed to develop according to the following stochastic process.

$$\log \theta_t = (1 - \rho_\tau) \log \theta + \rho_\tau \log \theta_{t-1} + \epsilon_t^\tau, \tag{A4}$$

$$\theta_t = \left(1 - \tau_t^h\right)^{-1}, \tag{A5}$$

where $\theta = 1/(1 - \tau^h)$ is the steady state value of θ_t (τ^h is the steady state value of τ_t^h). In this model, an increase in τ_t^h is interpreted as the intensification of labor supply constraints.

Household-Firm Matching and Two Labor Markets

At the beginning of each period, intermediate goods producing firm $j \in [0,1]$ is assumed to be randomly matched with one of the households. Therefore, the proportion of firms paired with households under supply constraints is τ_t^h. The proportion among these δ, thus,

$$\tau_t^f = \delta \tau_t^h \tag{A6}$$

of pairs are assigned to a "decentralized market" (the sets of households and firms in this market are denoted as H^D and F^D, respectively). Firms in this market are assumed to have no access to labor supplied by households outside their pair. Therefore, the labor input of firm $j \in F^D$ becomes $L_t(j) = \bar{L}$.

The remaining proportion of pairs $(1 - \tau_t^f)$ are assigned to the "centralized market" (the sets of households and firms in this market are denoted as H^C and F^C, respectively). Labor supplied by household $i \in H^C$ is aggregated as follows and used by firm $j \in F^C$.

$$L_t(j) = \left(\left(1 - \tau_t^f\right)^{-\lambda_t^w} \int_{H^C} L_t(i,j)^{1-\lambda_t^w}\, di\right)^{\frac{1}{1-\lambda_t^w}},$$

where $L_t(i,j)$ represents the labor input of firm j by household i, the multiplier $\left(1 - \tau_t^f\right)^{\frac{\lambda_t^w}{\lambda_t^w - 1}}$ is for normalization, and λ_t^w is the inverse of the wage elasticity of labor demand in absolute terms and follows the AR(1) process:

$$\log \lambda_t^w = (1 - \rho_w) \log \lambda^w + \rho_w \log \lambda_{t-1}^w + \epsilon_t^w. \tag{A7}$$

The cost minimization problem for firm $j \in F^C$ in the centralized market is given as follows.

$$\min_{L_t(i,j)} \int_{H^C} w_t(i) L_t(i,j)\ di$$
$$+ w_t(j) \left[L_t(j) - \left(\left(1-\tau_t^f\right)^{-\lambda_t^w} \int_{H^C} L_t(i,j)^{1-\lambda_t^w}\ di \right)^{\frac{1}{1-\lambda_t^w}} \right],$$

where $w_t(i)$ is the real wage for labor by household i, and $w_t(j)$ is the Lagrange multiplier. The solution of this problem is as follows.

$$L_t(i,j) = \left(1-\tau_t^f\right)^{-1} \left(\frac{w_t(i)}{w_t(j)}\right)^{-\frac{1}{\lambda_t^w}} L_t(j)$$

Then, we obtain the demand function for labor by household $i \in H^C$ by taking the integral of both sides of the above equation with respect to j:

$$L_t(i) = \left(\frac{w_t(i)}{w_t}\right)^{-\frac{1}{\lambda_t^w}} L_t, \tag{A8}$$

L_t is the average labor input in the centralized market, expressed as $L_t = \left(1-\tau_t^f\right)^{-1} \int_{F^C} L_t(j)\ dj$, and w_t $(= w_t(j)\ \forall j \in F^C)$ is the real wage index in the centralized market, expressed as follows.

$$w_t = \left\{ \left(1-\tau_t^f\right)^{-1} \int_{H^C} w_t(i)^{\frac{\lambda_t^w - 1}{\lambda_t^w}}\ di \right\}^{\frac{\lambda_t^w}{\lambda_t^w - 1}}.$$

This expression is obtained by substituting the solution of the cost minimization problem into the definition of $L_t(j)$.

Wage Setting

In the centralized market, the real wage $\overline{w}_t$ for labor by constrained household $i \in \overline{H}^C$ is assumed to be determined at the point where the labor demand curve in Equation (A8) intersects the vertical labor supply curve ($L_t(i) = \overline{L}$).

$$\overline{w}_t = \left(\frac{L_t}{\overline{L}}\right)^{\lambda_t^w} w_t. \tag{A9}$$

On the other hand, among household $i \in (H^C \setminus \overline{H}^C)$ not subject to labor supply constraints, the nominal wage of ξ_w of households is indexed to the previous period's inflation Π_{t-1} and the steady state inflation Π. Thus,

$$W_t(i) = \Pi_{t-1}^{\gamma_w}\Pi^{1-\gamma_w}W_{t-1}(i),$$

where γ_w is the proportion of households indexed to the previous period's inflation.

The remaining $1-\xi_w$ of households optimize their nominal wage W_t^* to maximize utility given the labor demand curve in Equation (A8). The first order condition yields the following:

$$(w_t^*)^{1+\frac{\eta}{\lambda_t^w}} = \frac{h_{1,t}}{h_{2,t}}, \tag{A10}$$

$$h_{1,t} = \frac{\chi}{\lambda_t^w} L_t^{1+\eta} w_t^{\frac{1}{\lambda_t^w}(1+\eta)} + \beta\xi_w E_t(1-\tau_{t+1}^h)\left(\frac{\Pi_t^{\gamma_w}\Pi^{1-\gamma_w}}{\Pi_{t+1}}\right)^{-\frac{1}{\lambda_t^w}(1+\eta)} h_{1,t+1}, \tag{A11}$$

$$h_{2,t} = \frac{1-\lambda_t^w}{\lambda_t^w} C_t^{-\sigma} L_t w_t^{\frac{1}{\lambda_t^w}} + \beta\xi_w E_t(1-\tau_{t+1}^h)\left(\frac{\Pi_t^{\gamma_w}\Pi^{1-\gamma_w}}{\Pi_{t+1}}\right)^{\frac{\lambda_t^w-1}{\lambda_t^w}} h_{2,t+1}, \tag{A12}$$

where $w_t^* = W_t^*/P_t$.

For simplicity, the wage of household $i \in H^D$ in the decentralized market is assumed to be identical to the wage of constrained household $i \in \overline{H}^C$ in the centralized market.

Firm

The intermediate goods producers $j \in [0,1]$ produces differentiated goods using labor. That is, the output $Y_t(j)$ of firm j is given by:

$$Y_t(j) = A_t L_t(j)$$

where A_t represents the technology level and follows the AR(1) process:

$$\log A_t = \rho_A \log A_{t-1} + \epsilon_t^A. \tag{A13}$$

Intermediate goods $Y_t(j)$ are combined as follows by final goods producers operating under perfect competition.

$$Y_t = \left(\int_0^1 Y_t(j)^{1-\lambda_t^p}\, dj\right)^{\frac{1}{1-\lambda_t^p}},$$

where λ_t^p is the inverse of the price elasticity of demand in absolute term, and follows the AR(1) process:

$$\log \lambda_t^p = \left(1-\rho_p\right)\log \lambda^p + \rho_p \log \lambda_{t-1}^p + \epsilon_t^p. \tag{A14}$$

From the cost minimization of final goods producers, the following demand function and price index P_t are derived.

$$Y_t(j) = \left(\frac{P_t(j)}{P_t}\right)^{-\frac{1}{\lambda_t^p}} Y_t. \tag{A15}$$

$$P_t = \left(\int_0^1 P_t(j)^{\frac{\lambda_t^p - 1}{\lambda_t^p}}\, dj\right)^{\frac{\lambda_t^p}{\lambda_t^p - 1}}.$$

Price Setting

Among firms in the centralized market (firm $j \in F^C$), the nominal price of ξ_p of the firms is indexed to the previous period's inflation Π_{t-1} and the steady state inflation Π. Thus,

$$P_t(j) = \Pi_{t-1}^{\gamma_p}\Pi^{1-\gamma_p} P_{t-1}(j),$$

where γ_p is the proportion of firms indexed to the previous period's inflation.

The remaining $1-\xi_p$ of firms optimize their nominal price (P_t^*) to maximize profits given the demand curve in Equation (A15). The first order condition yields the following:

$$p_t^* = \frac{x_{1,t}}{x_{2,t}}, \tag{A16}$$

$$x_{1,t} = \frac{1}{\lambda_t^p}\frac{w_t}{A_t} Y_t + \xi_p E_t\left(1-\tau_{t+1}^f\right)\Lambda_{t,t+1}\left(\frac{\Pi_t^{\gamma_p}\Pi^{1-\gamma_p}}{\Pi_{t+1}}\right)^{-\frac{1}{\lambda_{t+1}^p}} x_{1,t+1}, \tag{A17}$$

$$x_{2,t} = \frac{1-\lambda_t^p}{\lambda_t^p} Y_t + \xi_p E_t\left(1-\tau_{t+1}^f\right)\Lambda_{t,t+1}\left(\frac{\Pi_t^{\gamma_p}\Pi^{1-\gamma_p}}{\Pi_{t+1}}\right)^{\frac{\lambda_{t+1}^p - 1}{\lambda_{t+1}^p}} x_{2,t+1}, \tag{A18}$$

where $p_t^* = P_t^*/P_t$.

The real price $\bar{p}_t$ set by the firm in a decentralized market (firm $j \in F^D$) is assumed to be determined at the point where the demand curve in Equation (A15) intersects the vertical supply curve ($Y_t(j) = A_t\bar{L}$). That is,

$$\bar{p}_t = \left(\frac{Y_t}{A_t\bar{L}}\right)^{\lambda_t^p}. \tag{A19}$$

Central Bank

Monetary policy is assumed to be conducted according to the following Taylor rule,

$$\log R_t = (1-\phi_R)\log R\left(\frac{\Pi_t}{\Pi}\right)^{\phi_\pi}\left(\frac{Y_t}{Y}\right)^{\phi_y} + \phi_R \log R_{t-1} + z_t^R, \tag{A20}$$

where the monetary policy shock z_t^R follows the AR(1) process:

$$z_t^R = \rho_R z_{t-1}^R + \epsilon_t^R. \tag{A21}$$

Aggregation

Aggregating the demand function in Equation (A15) and substituting the production function of intermediate goods producers yields the following.

$$A_t\hat{L}_t = Y_t v_t^p, \tag{A22}$$

where $\hat{L}_t$ represents the total labor input for the economy, defined as follows.

$$\hat{L}_t = \int_0^1 L_t(j)\,dj = \tau_t^f\bar{L}_t + (1-\tau_t^f)L_t. \tag{A23}$$

v_t^p is defined as $v_t^p = \int_0^1 (P_t(j)/P_t)^{-\frac{1}{\lambda_t^p}}dj$, representing the variance of intermediate goods prices (i.e., the relative price distortion). v_t^p follows the dynamics[2]:

$$v_t^p = \tau_t^f(\bar{p}_t)^{-\frac{1}{\lambda_t^p}} + (1-\tau_t^f)(1-\xi_p)(p_t^*)^{-\frac{1}{\lambda_t^p}} + (1-\tau_t^f)\xi_p\left(\frac{\Pi_{t-1}^{\gamma_p}\Pi^{1-\gamma_p}}{\Pi_t}\right)^{-\frac{1}{\lambda_t^p}} v_{t-1}^p. \tag{A24}$$

[2] We use approximation: $v_{t-1}^p \approx \int_0^1 (P_{t-1}(j)/P_{t-1})^{-1/\lambda_t^p}dj$ in the calculation.

The real wage index for the economy is defined as $\widehat{w}_t \equiv \left\{\int_0^1 w_t(i)^{\frac{\lambda_t^w - 1}{\lambda_t^w}} di\right\}^{\frac{\lambda_t^w}{\lambda_t^w - 1}}$, and then the following relationship is derived.

$$\widehat{w}_t^{1-\frac{1}{\lambda_t^w}} = \tau_t^h \overline{w}_t^{1-\frac{1}{\lambda_t^w}} + (1-\tau_t^h)(1-\xi_w)(w_t^*)^{1-\frac{1}{\lambda_t^w}} + (1-\tau_t^h)\xi_w \left(\frac{\Pi_{t-1}^{\gamma_w}\Pi^{1-\gamma_w}}{\Pi_t}\widehat{w}_{t-1}\right)^{1-\frac{1}{\lambda_t^w}}. \quad \text{(A25)}$$

In addition, $\widehat{w}_t$, the real wage w_t in the centralized market, and the real wage $\overline{w}_t$ in the decentralized market are related by the following equation:

$$\widehat{w}_t^{1-\frac{1}{\lambda_t^w}} = \tau_t^f \overline{w}_t^{1-\frac{1}{\lambda_t^w}} + \left(1-\tau_t^f\right) w_t^{1-\frac{1}{\lambda_t^w}}. \quad \text{(A26)}$$

On the other hand, the price aggregation formula is as follows.

$$1 = \tau_t^f \bar{p}_t^{1-\frac{1}{\lambda_t^p}} + \left(1-\tau_t^f\right)\left(1-\xi_p\right)(p_t^*)^{1-\frac{1}{\lambda_t^p}} + \left(1-\tau_t^f\right)\xi_p \left(\frac{\Pi_{t-1}^{\gamma_p}\Pi^{1-\gamma_p}}{\Pi_t}\right)^{1-\frac{1}{\lambda_t^p}}. \quad \text{(A27)}$$

Finally, considering the government's budget constraints and aggregating household budget constraints yields the following.

$$C_t + G_t = \int_0^1 \frac{W_t(i)}{P_t} L_t(i)\, di + D_t,$$

where G_t represents external demand, and is determined as follows.

$$G_t = \zeta_t Y_t,$$

$$g_t = \frac{1}{1-\zeta_t}, \quad \text{(A28)}$$

$$\log g_t = \left(1-\rho_g\right)\log g + \rho_g \log g_{t-1} + \epsilon_t^g. \quad \text{(A29)}$$

The real firms' profit D_t is expressed as

$$D_t = Y_t - \tau_t^f \overline{w}_t \overline{L} - \left(1-\tau_t^f\right) w_t L_t,$$

on the other hand, labor income $\int_0^1 \frac{W_t(i)}{P_t} L_t(i)\, di$ is expressed as

$$\int_0^1 \frac{W_t(i)}{P_t} L_t(i)\, di = \tau_t^f \overline{w}_t \bar{L} + \left(1 - \tau_t^f\right) w_t L_t.$$

Therefore, the following resource constraints are derived.

$$C_t = (1 - \zeta_t) Y_t. \tag{A30}$$

Equilibrium Conditions

For the 28 variables

$$\{\Lambda_{t,t+1}, R_t, \Pi_t, d_t, C_t, \tau_t^h, \tau_t^f, \lambda_t^w, \overline{w}_t, \hat{L}_t, \widehat{w}_t, w_t^*, h_{1,t}, h_{2,t},$$

$$\lambda_t^p, A_t, \bar{p}_t, Y_t, p_t^*, x_{1,t}, x_{2,t,} z_t^R, v_t^p, L_t, \zeta_t, g_t, \theta_t, w_t\},$$

the following 28 equilibrium conditions are derived.

{(A1), (A2), (A3), (A4), (A5), (A6), (A7), (A9), (A10), (A11), (A12), (A13), (A14), (A16), (A17), (A18), (A19), (A20), (A21), (A22), (A23), (A24), (A25), (A26), (A27), (A28), (A29), (A30)}

Introducing Robots and AI

In period t, households are assumed to invest (I_t^Z) in robots and AI (Z_{t+1}) that will be traded in the next period at a real rental cost (r_{t+1}^Z). Thus, the household budget constraint can be rewritten as follows.

$$C_t(i) + \frac{B_t(i)}{P_t} + I_t^Z + \frac{\tau}{2}\left(\frac{I_t^Z}{Z_t} - \delta_Z\right)^2 + T_t = \frac{W_t(i)}{P_t} L_t(i) + R_{t-1}\frac{B_{t-1}(i)}{P_t} + r_t^Z Z_t + D_t,$$

where $\frac{\tau}{2}\left(\frac{I_t^Z}{Z_t} - \delta_Z\right)^2$ represents the adjustment cost for robots and AI investment (δ_Z is the depreciation rate of robots and AI). The transition equation for the stock of robots and AI is given as follows.

$$Z_{t+1} = (1 - \delta_Z) Z_t + I_t^Z.$$

On the other hand, the production function of intermediate goods producer $j \in [0,1]$ is replaced by the following:

$$Y_t(j) = A_t\left[\kappa Z_t(j)^{\frac{\phi-1}{\phi}} + (1-\kappa)L_t(j)^{\frac{\phi-1}{\phi}}\right]^{\frac{\phi}{\phi-1}}.$$

Similar to the baseline model, the labor input of τ_t^f of firm $j \in F^D$ at time t is constrained at $L_t(j) = \bar{L}$. However, unlike the baseline model, firms under constraints can adjust their output by adjusting their robots and AI input. Consequently, an alternative assumption regarding the price setting of these firms is required.

We assume that firms $j \in F^D$ under constraints also follow Calvo-type pricing. Specifically, we assume that only $(1-\xi_p)$ of the firms can optimize the nominal price $\bar{P}_t$. In this case, $\bar{P}_t$ is given by the following equation.

$$\bar{P}_t = \frac{\frac{1}{\lambda_t^p}\overline{mc}_t Y_t + E_t\sum_{s=1}^{\infty}\xi_p^s\Lambda_{t,t+s}\prod_{k=1}^{s}\left(\frac{\Pi_{t+s-1}^{\gamma_p}\Pi^{1-\gamma_p}}{\Pi_{t+s}}\right)^{-\frac{1}{\lambda_{t+s}^p}}\frac{1}{\lambda_{t+s}^p}\widehat{mc}_{t+s}Y_{t+s}}{\frac{1-\lambda_t^p}{\lambda_t^p}Y_t + E_t\sum_{s=1}^{\infty}\xi_p^s\Lambda_{t,t+s}\prod_{k=1}^{s}\left(\frac{\Pi_{t+s-1}^{\gamma_p}\Pi^{1-\gamma_p}}{\Pi_{t+s}}\right)^{\frac{\lambda_{t+s}^p-1}{\lambda_{t+s}^p}}\frac{1-\lambda_{t+s}^p}{\lambda_{t+s}^p}Y_{t+s}}$$

where $\widehat{mc}_{t+s}$ is the average marginal cost in period $t+s$, defined as $\widehat{mc}_{t+s} = \tau_t^f\overline{mc}_{t+s} + (1-\tau_t^f)mc_{t+s}$. $\overline{mc}_{t+s}$ represents the real marginal cost of firms operating under supply constraints and optimizing prices in period $t+s$, while mc_{t+s} represents the real marginal cost of firms not operating under supply constraints in period $t+s$.

Similarly, the optimal price P_t^* for the unconstrained firm can be expressed as follows.

$$P_t^* = \frac{\frac{1}{\lambda_t^p}mc_t Y_t + E_t\sum_{s=1}^{\infty}\xi_p^s\Lambda_{t,t+s}\prod_{k=1}^{s}\left(\frac{\Pi_{t+s-1}^{\gamma_p}\Pi^{1-\gamma_p}}{\Pi_{t+s}}\right)^{-\frac{1}{\lambda_{t+s}^p}}\frac{1}{\lambda_{t+s}^p}\widehat{mc}_{t+s}Y_{t+s}}{\frac{1-\lambda_t^p}{\lambda_t^p}Y_t + E_t\sum_{s=1}^{\infty}\xi_p^s\Lambda_{t,t+s}\prod_{k=1}^{s}\left(\frac{\Pi_{t+s-1}^{\gamma_p}\Pi^{1-\gamma_p}}{\Pi_{t+s}}\right)^{\frac{\lambda_{t+s}^p-1}{\lambda_{t+s}^p}}\frac{1-\lambda_{t+s}^p}{\lambda_{t+s}^p}Y_{t+s}}$$

Note that for the simulation, the values of the additional parameters in this model are set as $\kappa = 0.05$, $\tau = 1$, and $\delta = 0.04$.

2.2. Details of Estimation

Data and Observation Equations

For the seven exogenous shocks, the seven series of data listed in Table A2-1 are used (see Figure A2-1 for the time series developments). The sample period is from 1970/Q2 to 2025/Q1.

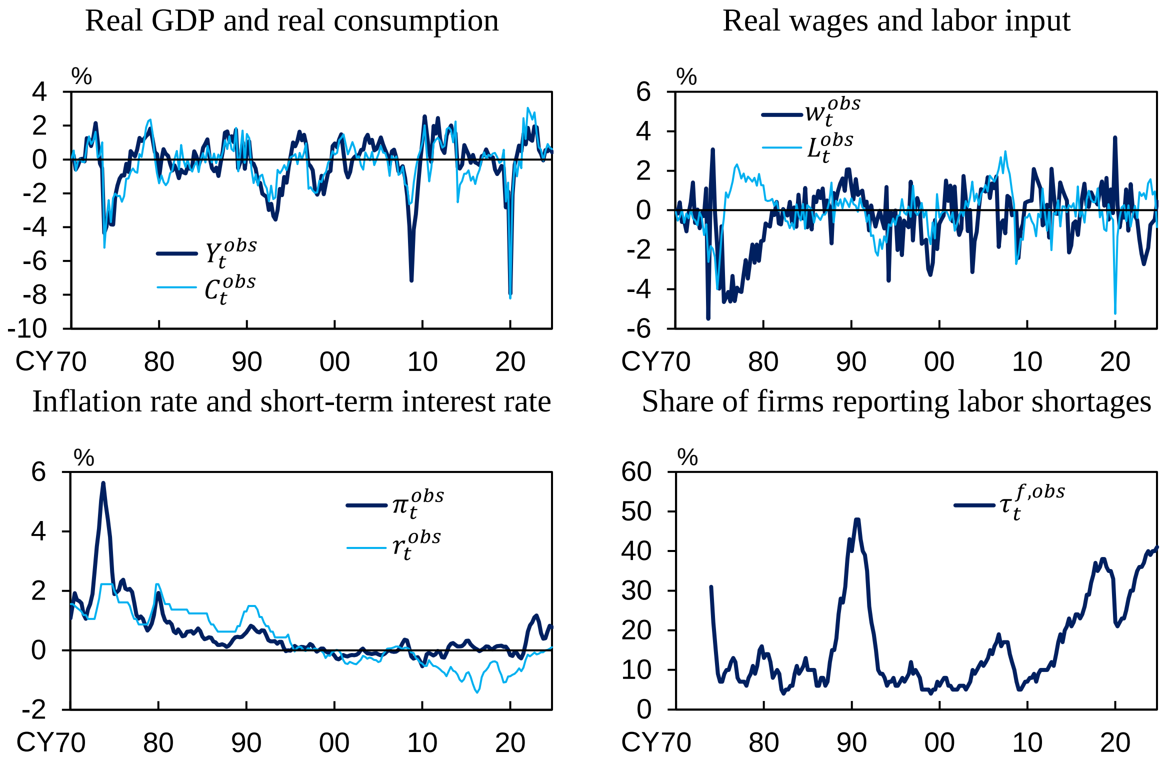
These observation data are linked to variables in the model through the following observation equations.

$$Y_t^{obs} = Y_t - Y,\ C_t^{obs} = C_t - C,\ L_t^{obs} = \hat{L}_t - \hat{L},$$
$$w_t^{obs} = \hat{w}_t - \hat{w},\ \pi_t^{obs} = \Pi_t - 1,\ r_t^{obs} = R_t - 1,\ \tau_t^f = c^\tau \tau_t^{f,obs}.$$

(Table A2-1) Data Used in the Estimation

Observation data	Notes	Sources
Real GDP per capita (Y_t^{obs})	Log of real GDP divided by the population aged 15 and over. Figures are detrend using a one-sided HP filter (seasonally adjusted).	Cabinet Office; Ministry of Internal Affairs and Communications.
Real consumption per capita (C_t^{obs})	Log of real household final consumption expenditure divided by the population aged 15 and over. Figures are detrend using a one-sided HP filter (seasonally adjusted).	Cabinet Office; Ministry of Internal Affairs and Communications.
Labor input (L_t^{obs})	Log of regular employees multiplied by total working hours. Figures are detrend using a one-sided HP filter (seasonally adjusted).	Ministry of Health, Labour and Welfare.
Real hourly wages (w_t^{obs})	Log of real total cash earnings, deflated by the CPI (excluding fresh food and energy) and divided by total working hours. Figures are detrend using a one-sided HP filter (seasonally adjusted).	Ministry of Health, Labour and Welfare.
Inflation rate (π_t^{obs})	Seasonally adjusted quarter-on- quarter change in the CPI (excluding fresh food and energy). The effects of consumption tax hikes are excluded as level shifts.	Ministry of Internal Affairs and Communications.
Short-term interest rate (r_t^{obs})	The basic loan rate of the Bank of Japan is used before 1994, and the shadow rate from Krippner (2013) is used after 1995.	Haver.
Share of firms reporting labor shortages ($\tau_t^{f,obs}$)	Share of firms reporting "shortages" in the *Tankan* survey's employment assessment (all enterprises and all industries). Figures prior to 1974/1Q are missing.	Bank of Japan

(Figure A2-1) Time Series Developments of Data



Sources: Cabinet Office; Ministry of Internal Affairs and Communications; Ministry of Health, Labour and Welfare; Bank of Japan; Haver; Krippner (2013).

Estimation Method

Bayesian estimation is used for model estimation. Specifically, the likelihood function is derived by applying the Kalman filter after representing the model in state-space form. The density function of the posterior distribution is then numerically calculated by combining the prior distributions of the parameters. For this numerical calculation, the Markov Chain Monte Carlo (MCMC) method is employed, specifically using the Metropolis-Hastings (MH) algorithm. A total of 200,000 MCMC samples are drawn, with the first 100,000 samples discarded[3].

The prior distributions of parameters are set as shown in Table A2-2, according to Hirose and Kurozumi (2012), who estimated a DSGE model using Japanese data. The prior distributions for parameters specific to this paper are set as follows. The prior distribution for c^{τ}, the ratio of $\tau_t^{f,obs}$ to τ_t^{f}, is set as a relatively neutral beta distribution with mean 0.5 and standard deviation 0.2. The prior distribution for δ, the ratio of τ_t^{f} to τ_t^{h} is similarly set. The prior distribution for τ^{h}, the steady-state value of τ_t^{h} is set to a beta distribution with mean 0.1 and standard deviation 0.05, considering that the median of $\tau_t^{f,obs}$ during the estimation period is approximately 0.10. The prior distribution for ψ

[3] Dynare (Adjemian et al., 2024) was used for model estimation.

for the ratio of $\bar{L}$ to $\hat{L}$ is set to a beta distribution with mean 0.1 and standard deviation 0.05, considering that the minimum of L_t^{obs} is around -0.05 and the model assumption that $\bar{L}$ is always smaller than $\hat{L}_t$.

Additionally, the subjective discount rate β is set to 0.995, and the steady-state value ζ of the external demand to GDP ratio is set to the average during the estimation period. The steady-state values λ^p and λ^w for the price markup rate and wage markup rate, respectively, are set to 1/6, consistent with the calibration of λ^w in Hirose and Kurozumi (2012).

(Table A2-2) Prior and Posterior Distributions of Parameters

		Prior distributions			Posterior distributions	
		Distribution	Mean	S.D.	Mean	90%CI
σ	Inverse of intertemporal elasticity of substitution for consumption	Gamma	1	0.375	1.84	[1.32, 2.31]
η	Inverse of elasticity of labor supply	Gamma	2	0.75	1.26	[0.52, 1.94]
ξ_p	Calvo parameter of prices	Beta	0.375	0.1	0.90	[0.89, 0.91]
ξ_w	Calvo parameter of nominal wages	Beta	0.375	0.1	0.53	[0.45, 0.61]
γ_p	Price indexation	Beta	0.5	0.2	0.88	[0.79, 0.98]
γ_w	Wage indexation	Beta	0.5	0.2	0.85	[0.72, 0.98]
ϕ_R	Interest rate inertia	Beta	0.5	0.2	0.81	[0.76, 0.86]
ϕ_π	Response of interest rate to inflation rate	Gamma	1.7	0.1	1.71	[1.57, 1.86]
ϕ_y	Response of interest rate to real GDP	Gamma	0.125	0.05	0.48	[0.36, 0.59]
ρ_A	Persistence of technology shock	Beta	0.5	0.2	0.70	[0.64, 0.76]
ρ_g	Persistence of external demand shock	Beta	0.5	0.2	0.84	[0.76, 0.92]
ρ_p	Persistence of price shock	Beta	0.5	0.2	0.73	[0.64, 0.82]
ρ_w	Persistence of wage shock	Beta	0.5	0.2	0.03	[0.00, 0.05]
ρ_d	Persistence of preference shock	Beta	0.5	0.2	0.89	[0.85, 0.93]
ρ_R	Persistence of monetary policy shock	Beta	0.5	0.2	0.75	[0.66, 0.83]
ρ_τ	Persistence of supply constraint shock	Beta	0.5	0.2	0.97	[0.96, 0.99]
c^τ	Ratio of $\tau_t^{f,obs}$ to τ_t^f	Beta	0.5	0.2	0.15	[0.04, 0.27]
τ^h	Steady-state value of τ_t^h	Beta	0.1	0.05	0.04	[0.02, 0.07]
ψ	Ratio of $\bar{L}$ to $\hat{L}$	Beta	0.1	0.05	0.09	[0.03, 0.16]
δ	Ratio of τ_t^f to τ_t^h	Beta	0.5	0.2	0.62	[0.35, 0.89]
Π	Steady state inflation rate	Normal	1.006	0.0005	1.006	[1.005, 1.007]
σ_R	Standard deviation of monetary policy shock	Inv-Gamma	0.5	Inf	0.15	[0.13, 0.17]
σ_A	Standard deviation of technology shock	Inv-Gamma	0.5	Inf	0.82	[0.76, 0.89]
σ_g	Standard deviation of external demand shock	Inv-Gamma	0.5	Inf	0.67	[0.62, 0.73]
σ_p	Standard deviation of price shock	Inv-Gamma	0.5	Inf	0.24	[0.17, 0.30]
σ_w	Standard deviation of wage shock	Inv-Gamma	0.5	Inf	0.31	[0.22, 0.40]
σ_d	Standard deviation of preference shock	Inv-Gamma	0.5	Inf	3.82	[2.95, 4.61]
σ_τ	Standard deviation of supply constraint shock	Inv-Gamma	0.5	Inf	0.63	[0.25, 1.00]